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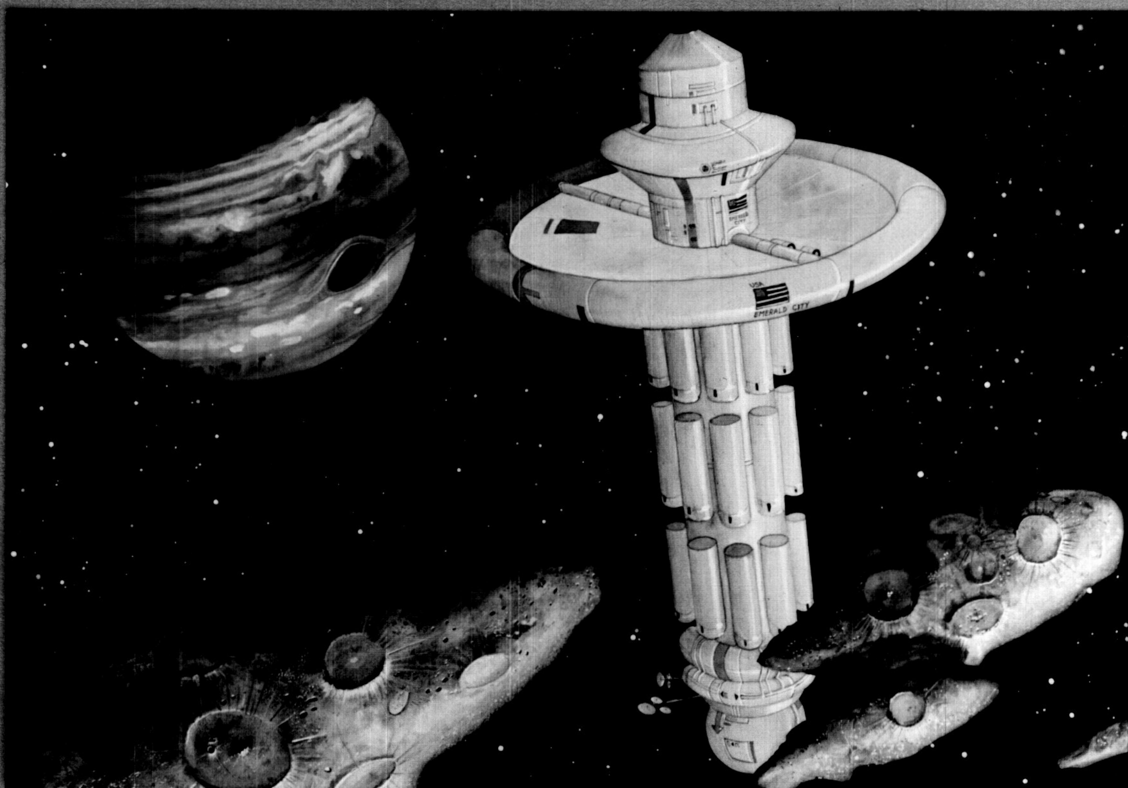
PROJECT WISH: THE EMERALD CITY



THE OHIO STATE UNIVERSITY

Department of Aeronautical and Astronautical Engineering

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PROJECT WISH:
THE EMERALD CITY

June 1990

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ABSTRACT

The preliminary design of a permanently manned autonomous space oasis (PEMASO), including its pertinent subsystems, was performed during the 1990 Winter and Spring quarters. The purpose for the space oasis was defined and the preliminary design work was started with emphasis placed on the study of orbital mechanics, power systems and propulsion systems. A rotating torus was selected as the preliminary configuration and overall size, mass and location of some subsystems within the station were addressed. Computer software packages were utilized to determine station transfer parameters and thus the preliminary propulsion requirements. Power and propulsion systems were researched to determine feasible configurations and many conventional schemes were ruled out. Vehicle dynamics and control, mechanical and life support systems were also studied. For each subsystem studied, the next step in the design process to be performed during the continuation of the project was also addressed.

ACKNOWLEDGEMENTS

We would like to express our sincerest appreciation to Karl Faymon and Lisa Kohout from the NASA Lewis Research Center in Cleveland, Ohio, for all the information and support they provided throughout the year. Our thanks are also extended to Kurt Hack and John Riehl from NASA Lewis Research Center for providing us with and helping us use the trajectory optimization computer codes. We are also grateful to Dr. Peter Turchi for his input with propulsion and power. Thanks to Gary Hufford for his help as well.

FOREWORD

Project WISH is about the design of a Permanently Manned Autonomous Space Oasis (PEMASO). It is a three-year design effort under the Advanced Space Design Program sponsored by NASA/USRA. This report presents the developments through the first year of the project. The project will continue over the next two years improving and refining the previous year's design studies, and bringing in additional aspects not considered during the first year.

For the first year of the project, the objective was to identify important parameters and issues for each subsystem as they relate to the mission requirements for PEMASO, and to begin to obtain preliminary figures for these parameters. Subsequently, the effort has been directed towards developing an understanding of how the subsystem designs would interact with each other to design the overall system. This point marks the end of the first year's effort. Next year, the second phase of Project WISH will focus on integrating the design parameters of each one of the subsystems to determine optimum design point values from the system-level perspective for the space oasis. The third year's effort will be on detailed design of subsystems for the total system.

This report is the result of Winter-1990 and Spring-1990 design courses, AAE 515 "Preliminary Design of Flight Vehicles", and AAE 416 "Design of Flight Vehicles", respectively. For the Winter-1990 quarter, there were three design teams of six students each. Each team worked on the design independently and developed their own understanding of the scope of the project. For the Spring-1990 quarter, all the teams were combined and the whole class worked on a single design incorporating and combining the results from the winter quarter. Groups for nine subsystems were identified within this frame and each student was charged with responsibility in two subsystem groups.

In comparison to existing design studies, we opted for a unique topic to study within the USRA Advanced Space Design Program. The design topic of a Permanently Manned Autonomous Space Oasis fits into a combination of areas: Exploration of the Solar System and Orbiting Facilities. Hence, the design activities under this project are tailored not only to give our students a broad context within which to address specific design issues with a multi-disciplinary approach, but to also give them a creative stimulus to realize what may otherwise seem a "romantic fantasy". This way, the Emerald City of Project WISH provides our students with a realistic design experience as well as enjoyment of their fantasy into the near-future. Both elements are intertwined to enrich the education of our students.

We gratefully acknowledge the support given to us throughout the year by our mentors, Dr. Karl A. Faymon and Ms. Lisa Kohout of NASA-Lewis Research Center. In addition, I would like to thank my colleagues Drs. Rama K. Yedavalli, Thomas M. York and Peter Turchi of the Aeronautical and Astronautical Engineering Department of The Ohio State University for their assistance and advice during the year.

Dr. Hayrani Öz, June 1990

PRELUDE

Toward the end of the year, a few of the students volunteered to write about the Emerald City. The following are five short stories written to give some perspective on missions that might be carried out. Come on a journey through the solar system with us as we board the Emerald City....

Mission to Venus

The Emerald City is alive with activity today. A few hours ago, the communication system received an emergency call from Venus. One of the atmosphere converters, which create an earth-like environment, is malfunctioning. Although emergency assistance is being provided from Space Station Freedom, the quantity of materials for the repair can only be obtained from asteroids. Thus, we will be supplying the needed materials to repair the converter.

We will also be supplying the colony with much needed personnel for the recently completed production plant. I will be studying the effects of velocity and inertia changes on the inhabitants of the Emerald City as we make our journey to Venus. Once we reach the planet, I will take residence and study what effects, if any, the atmosphere converters have had on the colonists. Once the repairs are made and the supplies and personnel are unloaded, the Emerald City will depart on a mission to some other sector of the solar system.

–Michelle Strosky

Rendezvous With A Comet

The Emerald City drifts lazily in an orbit around the Sun near the planet Venus. Having just performed several months of extensive construction on the Venitian landscape to prepare for the expansion of a space colony, the crew members aboard the spacecraft are ready for a change. As if from an infinitely distant beacon, the continuous communication link from the Earth to the Emerald City begins as a tiny point in the darkness of space and spreads to a violet haze as it reaches the Emerald City. Traveling on this intense beam of laser light is an urgent message stating that the old Hubble space telescope, long since overhauled, upgraded, and placed in an orbit around Mars, has detected a formerly undiscovered comet racing toward the planet Neptune. The Emerald City is being ordered to get as close as safely possible to Neptune, so as to observe and perform experiments on the resulting impact of the comet and the planet's gaseous surface.

The orbital trajectory computers immediately go to work, determining the optimal transfer orbit for a rendezvous with the future event. At the same time, Chief Engineer Edse in the Propulsion Control Center carefully programs the massive computer systems for yet another orbit transfer. The gigantic spacecraft gradually gains speed as its antimatter propulsion thrusters accelerate the ship into its three year orbit transfer.

Hurtling through space, some of the crew in the spacecraft's industrial center begin to construct the necessary equipment to monitor the comet's impact. Still others begin regular maintenance on the shuttle craft's resupply and docking apparatus, having been under a strenuous workload during the expansion of the Venus colony.

For the Emerald City, this is just another of the numerous important assignments it has undertaken in the last forty years. Continuing along on its mission to expand and explore, who knows what will be the next task.

–Gary Krock

The Rare Mission to Pluto

It's 2005 and the scientists are really excited. Due to planetary alignment, the Emerald City will be able to fly out to Pluto on a low fuel, 3-year mission. (Really the fuel is rather high since we usually keep our missions closer to the sun.) It looks like the Far Seeker, the most complex, robot-manned telescope, will finally find a home way out there... beyond all the noise of the solar system. Who knows, maybe it will be capable of finding that elusive 10th planet we've been kind of searching for.

Our ship has been reconfigured for extra hydrogen propellant but we don't need any extra antimatter. Antimatter! That stuff is so potent, a little goes a long way. Speaking of reconfiguring, there were an extra 50 technologists added to this crew to rebuild the telescope and to set up communications links to the home base on Planetoid Ceres. If you ask me, I'm not sure how they are going to get the telescope onto the shuttle. They're just building, building, building. They're all such geeks, too. I wonder if they're even capable of EVAing to set up the telescope.

I think the best thing to our credit is the unique entertainment and recreational facilities we have to show all these greenhorn space travelers. We, the 500 people who make up the crew, take for granted the psychadelic volleyball, stumbling horseshoes, low gravity basketball, and some of those other games. But we love to show them off.

–Eric Strobel

MISSION CRITICAL: Beer Run to Ceres

If someone were to look upon the asteroid from any great distance, the colony would barely be noticeable. Since humanity had made its presence known in the solar system some forty years ago, mining on the various asteroids orbiting the star Sol had been going on. The small mining colony on the barren asteroid of Ceres consisted of five dome shaped buildings, each large enough to house about fifty or so people. Mining took place just outside the metallic structures where raw iron ore was extracted to be refined for use on other colonies of Sol's satellites. In a scant few weeks, the central dome would be filled with colored lights and drunken revelers celebrating the twenty-fifth year the mining colony was in existence. The man in charge of the celebration, a short balding man by the name of Jonesy, had one worry, would the beer arrive in time and would there be enough? The best beer in the solar system was no longer brewed on Earth, but was now brewed on Venus, and Jonesy wanted the best.

The Emerald City, begun as Project Wish, was due to rendezvous with Ceres in fifteen days, but Jonesy didn't like to cut things that close. The Emerald City was an old ship, but was the first colony of humankind in the solar system. The people living in the Emerald City were nomadic, moving from place to place within the solar system, going wherever they were needed. This time they were called to ship kegs of beer from the brewery on Venus to the mining colony on Ceres.

Fifteen days later, the Emerald City arrived on time. The shuttle craft, loaded with kegs of **Venus' Best**, detached from the tip of the Emerald City and landed on Ceres where men were able to carry two kegs at a time due to the reduced gravity on the asteroid. Soon, the shuttle was emptied and the celebration was begun. Jonesy was happy, and so was the populace of the Emerald City that served the citizens of the solar system.

–Andy Szmerekovsky

A Day in the Life...

Rosalie's job in the Emerald City had to do with food production. When she got to work, she adjusted the lighting of the plant area. It was a huge room with a high ceiling that had many lights and water sprinklers suspended from it. The far wall was curved and it was a solid section that could be receeded to reveal a window that was as big as the entire wall. This was to utilize sunlight when possible to save on power. The wall was only partially opened since the city was in the shadow of a large asteroid and very little sunlight shown through, but the view of the stars was always breathtaking to Rosalie.

She could see the asteroid that they were mining for oxygen. They were almost finished and would soon be powering the propulsion system to move on to rendevous with one of the Earth's interplanetary space cruisers. It takes off from Space Station Freedom and is probably already on it's way. They'll rendevous near Mars to transfer the oxygen and Rosalie's excited because one of her friends from college is part of the crew and promised to bring a few of the newly released movies.

–Linda Slonksnes

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CHAPTER 1

INTRODUCTION AND PROJECT BACKGROUND

1.0 INTRODUCTION

The 21st century is now coming to a close. The U.S. space program has put colonies on the moon, Venus, Mars, and several moons of Jupiter and Saturn. We are in a nominal orbit between Mars and Jupiter, just outside the asteroid belt. We are preparing for a mission to Venus. Last week, we received a call on the emergency frequency that the atmosphere converters were malfunctioning. In addition to taking mechanics and repair equipment, we will also be supplying Venus with much needed personnel and building supplies for a new production plant.

1.1 MISSION SPECIFICATIONS

This scenario is just one of many missions that the Emerald City of Project WISH (Wandering Interplanetary Space Harbor) is capable of executing. When the idea of a planetary wanderer was conceived, some constraints were to be incorporated into the design. To supply the colonies with people and supplies, the ship must serve as a permanent living quarters for 500-1000 people. Therefore, a self-enclosed ecological system must be created. Also, the ship is to transport goods and services throughout the solar system so it must be totally autonomous of Earth. However, the ship can use any resources available in the solar system, such as metal ores from the asteroids, regolith from the moon, and oxygen from the Martian moon, Phobos. To support and serve the colonies, the ship must also be designed for a lifetime of at least fifty years. In addition, the station must be able to travel anywhere in the solar system in three years. This travel time was chosen so that support can be given to any of the colonies in a relatively short period of time.

1.2 OVERVIEW

The following report consists of the three major factors in the development of the Emerald City. First, many trajectories are defined and analyzed to determine the velocity changes necessary for any mission desired in the solar system. Then, a nominal orbit is chosen based on the power, propulsion, and resupply requirements. The propulsion system follows the orbital mechanics because the two are interrelated. The thrust requirements for the propulsion system are dependent upon the change in velocity requirements to move from one point to another point. A propulsion system is recommended based on these parameters. The Emerald City is too large to be considered a rigid body, therefore analysis of the dynamics and control is considered. Then, the life support system is laid out in detail. Many factors such as environment management, waste management, and agriculture are considered. To support life for both plants and people, the life support system is an enclosed ecological system; Directly related to the mental and physical health of the inhabitants of the Emerald City, the support systems provide the communications necessary to talk with other people on the earth and on the colonies. The problem of radiation and how to shield against it is also looked at in this section. Also, to resupply goods, services and people, the shuttle and maintenance are considered. The power system provides the electrical power to run the entire ship. Whether large or small, all systems on the ship depend on the power system. Dynamics and control rely on it to keep the ship in the proper position; life support relies on it to keep the management systems running; and the communication system relies on it to provide the communication necessary for the people. Next, the thermal control radiator is recommended. This will provide a means of dissipating the waste heat produced by the power system, equipment, inhabitants, and the heat collected from the sun and planets. Finally, everything is put together. All of the components are combined to form a preliminary configuration of the Emerald City. However, this is not the final design of the Emerald City. This is only the beginning. The work done this year paved the way for more detailed analysis to be done in the next two years.

Project WISH should become operational around the middle of the 21st Century. Table 1.1 shows an envisioned time-line for the project as compared to other previous and concurrent ventures.

Table 1.1: Envisioned Time-line of Project WISH in Relation to Other Projects

1990	- President Bush announces Mars Initiative to reach the Red Planet in 30 years.
1991	- NASA presents a program to send sensing probes throughout the solar system. Projects include the return to the inner solar system, exploration of the asteroid belt, and further missions to the outer planets.
1996	- Space Station Freedom becomes operational.
1998	- Heavy Lift Launch Vehicle makes its maiden flight.
2000	- Construction begins on a near-geosynchronous Earth orbit space station.
2005	- U.S. returns to the moon.
2010	- Construction begins on the Moon Base. - Maiden flight of National Aerospace Plane.
2015	- Moon Base becomes fully operational.
2020	- First manned mission to Mars.
2023	- First living modules constructed on Mars. - Construction begins on Reusable Interplanetary Ships (R.I.S.) for carrying personnel and cargo.
2028	- Mars Base becomes fully operational.
2030	- R.I.S.'s becomes operational.
2040	- Implementation of Project WISH.
2045	- Unmanned probe sent to Alpha Centari.
2050	- The Emerald City becomes operational.

CHAPTER 2

ORBITAL MECHANICS

2.0 INTRODUCTION

Project WISH, the Wandering Interplanetary Space Harbor, was given several mission parameters to help define a more solid idea of what the spacecraft would need to be like. The orbital mechanics group looked at the requirement that the Emerald City was to travel anywhere within the solar system, and it was to do so in a maximum of three years. A feasibility study was started to find the shapes and velocities of transfer orbits needed and to determine a nominal park orbit for the Emerald City to stay in when it was not travelling. In this study, the magnitude and directional changes in velocity (labelled ΔV) from one orbit to a transfer orbit to another orbit were calculated to determine the maximum and minimum values that would need to be considered by the propulsion group.

2.1 TRAJECTORY ANALYSIS

The mission requirement given was that the ship was to travel anywhere within the solar system in a maximum of three years. An impulse-optimizing computer program was used to show the worst case scenarios around the solar system. By looking at transfers from one planet to its neighbors, at points around its full orbit for a given transfer time of three years, some sample worst cases were drawn up. The sample data showed that Saturn appears to have the lowest worst case velocity change of 42.4 km/s. ΔV's to planets inside of Saturn's orbit may be lowered by reducing the flight time, as three years was given as the maximum. Because the Emerald City's mass is expected to be so large and none of the propulsion systems would be likely to handle some of the worst case scenarios for the most outside planets, the orbit of Saturn was chosen as the outermost nominal distance for the Emerald City to fly. Low ΔV trips to Uranus, Neptune, and Pluto may be made, but they would be only special trips, and may require extensions to the flight time limit.

Adding to the problem of high velocity changes, gravitational effects and finite burn times raise the initial values of the ΔV's. The Mulimp II computer program[1] assumes instantaneous accelerations from the speed of the planet the ship was near to the needed speed and direction that would put it in its transfer orbit. A factor from 1.5 to 2 was multiplied to the instantaneous values to take care of the gravitational effects. The value of two was obtained from the computer program Chebytop[2] that took gravitational effects into consideration when giving the ΔV's for a constant acceleration mission. When compared with the instantaneous ΔV values of the impulse optimizing computer program, the values were roughly doubled. An approximate value of 75 to 100 km/s was taken for the worst case total delta-V, and 50 km/s for any acceleration or deceleration.

A set of nondimensionalized graphs were drawn up to relate I_{sp} and ΔV by the equation

$$\frac{m_l}{m_o} = e^{-\frac{\Delta V}{I_{sp} g}} - \frac{(I_{sp} g)^2}{2\alpha t_{pr}}\left(1 - e^{-\frac{\Delta V}{I_{sp} g}}\right) \qquad (2.1)$$

using the payload mass ratio, m_l/m_0, and specific energy, αt_{pr}, as parameters. In this equation, m_l is the payload mass, m_0 is the initial mass, α is specific power, and t_{pr} is the burn time. Initial values of m_l/m_0 = .2 and αt_{pr} = 25 x 10^9 were chosen as optimal values. From the graphs, found in Figures 2.1, 2.2 and 2.3, a ΔV of 50 km/s can be shown to need an I_{sp} of 3330 seconds; a ΔV of 100 km/s, 8340 seconds. The three graphs show a complex relationship between burn time (because the specific power, α, is constant), payload mass ratio, I_{sp}, and ΔV. To try to reduce the magnitude of the ΔV for some cases, a fly-by chart was made from the planetary positions at given time intervals, given by the impulse optimizing computer program. The

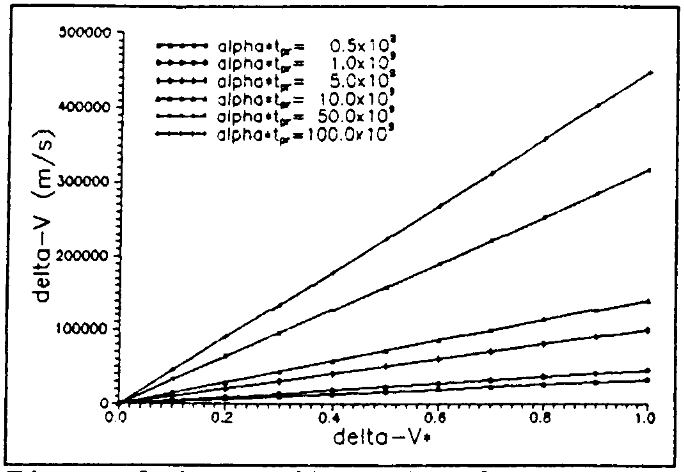


Figure 2.1: Nondimensional ΔV vs. ΔV with αt_{pr} as a Parameter

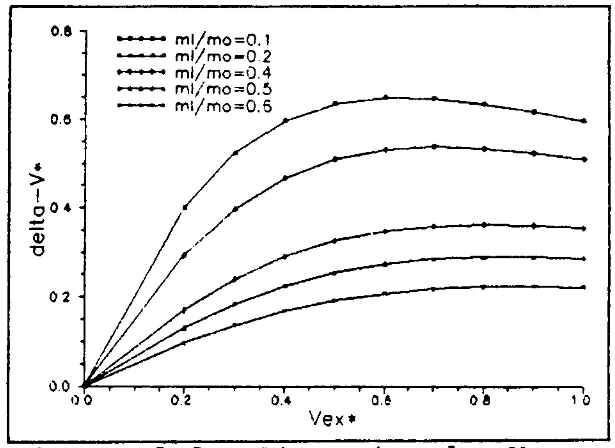


Figure 2.2: Dimensional ΔV vs. Exit Velocity with the Payload Mass Ratio as a Parameter

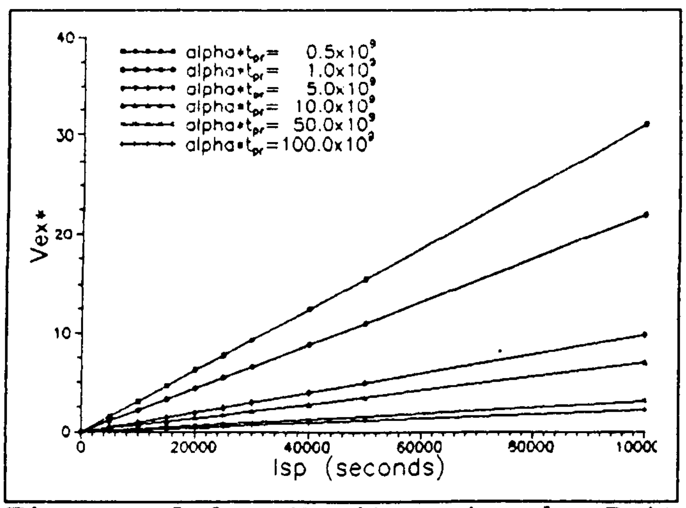


Figure 2.3: Nondimensional Exit Velocity vs. Specific Impulse with αt_{pr} as a Parameter

graph showed the X-Y positions of the planets over a documented range of times starting at the year 2000 until they ran their orbits. Given the starting and ending positions and dates, transfer orbits were found and compared with the positions of the other planets in the same time range. If a planet is close enough for a flyby, it can lower the ΔV's needed at each impulse point. This decreases the performance expected of the propulsion system. Usually, though, the total ΔV for the mission goes up, because there are more impulses. This raises the amount of fuel needed for the transfer. Individual missions must be looked at to see whether flybys would be more or less beneficial.

It is hoped that a more complete analysis of the ΔV required for a finite burn time, including gravitational effects will yield lower required ΔV's. If that can be achieved, the prospect of expanding the nominal outer boundary of flight to Uranus can be looked at. Also, the specific energy and, hence, the burn time can be lowered to a more optimal value that may lower the necessary I_{sp}, or allow the payload mass ratio to increase.

2.2 NOMINAL ORBIT

Another mission requirement imposed on Project WISH stated that a nominal orbit must be found for the Emerald City. Since there was no reason given for having a nominal orbit, a variety of orbital shapes and uses were considered. A highly elliptical orbit was looked at. Its perihelion was near Venus, and its aphelion near Saturn. It was suggested as a fast way to ride into and out of the center of the solar system. Unfortunately, the orbital period was 42 years, almost the minimum design life of 50 years for the ship. A circular orbit at 3.2 AU on the ecliptic plane has been chosen as a preliminary value. The orbit is to be used for maintenance and resting between missions. It will also be good for communications, as any colonies that need use of the ship will have approximate knowledge of where the ship is when it is not being used.

The value of 3.2 AU was chosen because it put the ship close to the edge of the asteroid belt (within 10 million miles of the outer edge), and within easy reach of the moons of Jupiter (depending on where the ship is in its orbit). Concentrated supplies of valuable metals, needed for repair, and light atoms (hydrogen and helium), needed for propellant, can be found in both of these places. The value of the radius is subject to change, given the needs of the different subsystems. Vehicle dynamics and control may find the stability is bad, communications may think the asteroid belt has a hampering effect on the transmissions, and/or shielding may discover that the area is still too dirty with asteroid debris.

For these reasons, only a cursory attempt was made to deliver a preliminary nominal orbit. It is hoped that it will be possible to optimize a better, more fully functioning orbit off of these values as the project is studied further.

CHAPTER 3

PROPULSION SYSTEM

3.0 INTRODUCTION

The propulsion system of the Emerald City is one of the major subsystems that has been studied during the development of Project WISH. Looking at an overview of the entire project, the question of propulsion stands out as one of the pivotal factors in accomplishing Project WISH. An effective propulsion system that enables the Emerald City to satisfy its mission requirements is essential if it is to have credibility as a viable mode of interplanetary travel and support. Factors such as specific mission specifications, availability and developmental capacity of the technology, and interactions with other ship systems must be considered when choosing the system that will propel the station to its far-flung destinations.

The selection of a propulsion system for the Emerald City was broken down into five major phases. The first phase consisted of the identification of mission and design requirements and their effects on the propulsion system analysis. The second phase was an investigation into the mathematical and physical background of propulsion with the hopes of developing connections between the mission specifications and important design parameters. A general-level survey of several propulsion systems constituted the third phase of the process, while the fourth phase was a more in-depth study of propulsion systems that were deemed promising by the general-level study. The fifth phase involved the final recommendation and analysis of the system that seemed to offer the best solution to the propulsion problem of Project WISH.

3.1 DESIGN REQUIREMENTS AND GUIDELINES

The first phase of the design process was the identification of critical mission and design requirements and their effects on propulsion. The mission of Project WISH is to expand and support the human presence in the solar system. In addition to this demanding task, there were also design objectives detailed in Section 1.1 to be met. These mission and design objective requirements have a profound impact on the design of the propulsion system, and are summarized in Table 3.1. These important factors, plus many other lesser points had to be carefully considered in the design of the propulsion system for Project WISH.

With the guidelines of Table 3.1 established, some theoretical and mathematical background of the phenomenon of propulsion was explored with the hope of relating the information in Table 3.1 to physical design parameters of the engines.

3.2 THEORETICAL BACKGROUND

Thrust is obtained from a standard rocket engine by the expulsion of mass at a high exit velocity from a vehicle. This force can be calculated from the well-known formula

$$T = \dot{m}V_e \qquad (3.1)$$

Table 3.1: Effect of Mission Requirements on Propulsion Design

MISSION REQUIREMENTS	CONSIDERATIONS FOR PROPULSION
1) Must have an operational lifetime of at least fifty years	Lifetime, serviceability, maintainability, replacement capacity
2) Three year maximum flight time from and to anywhere in the solar system	Thrust levels and deliverable impulse
3) Fully autonomous	Location, processing, and resupply of working materials (fuel, propellant, coolant)
4) Support between 500 - 1000 people, supplies, and heavy equipment for planetary bases	Thrust levels and deliverable impulse to accelerate a massive payload sufficiently

for values of propellant mass flow rate, $\dot{m}$, and exit velocity, V_e. It can be seen from this equation that there are two basic ways to increase thrust; by expelling more mass per unit time or by increasing the velocity at which the mass is expelled. Unfortunately, both of these methods have some drawbacks to them. Increasing the mass flow rate implies that the propellant mass will go up while increasing the exit velocity usually results in a more massive propulsion system. A compromise that yields the best thrust for the smallest propellant mass and propulsion system mass should be reached for the optimum engine design.

With the above discussion in mind, a very important parameter can be introduced, namely the specific impulse, or I_{sp}. The definition of I_{sp} is the total impulse generated per unit weight of propellant, or

$$I_{sp} = \frac{J}{W_p} = \frac{T}{\dot{m}g} = \frac{V_e}{g} \qquad (3.2)$$

where J is the impulse, T is the thrust of the engine, and W_p is the weight of propellant expelled. The significance of the I_{sp} is that it provides a measure of how much propellant mass is required to generate a given thrust; the higher the I_{sp}, the less propellant mass that is required. This is an important factor when large amounts of thrust are needed to accomplish a mission because, if the I_{sp} is too low, the mass of propellant required will make the mission impossible. An important equation that shows the importance of I_{sp} as a parameter is the ratio of propellant mass, m_p, to initial mass, m_0, referred to as the propellant mass ratio. This equation states

$$\frac{m_p}{m_o} = 1 - e^{-\frac{\Delta V}{I_{sp} g}}. \qquad (3.3)$$

Thus, the variation of propellant mass ratio with ΔV and I_{sp} can be determined and is shown in Figure 3.1. This figure shows the impact that the I_{sp} has on the propellant mass. For a mission requiring a ΔV of 50 km/s, a station using an engine with an I_{sp} of 500 seconds would initially consist of over 99 % propellant by mass. However, a station attempting the same mission using an engine with an I_{sp} of 5000 seconds would initially consist of about 60 % propellant.

Another ratio of importance is the payload mass ratio, or m_l/m_0. Defined as the ratio of ship payload mass without the dry mass of the propulsion unit to initial mass, this equation is given by

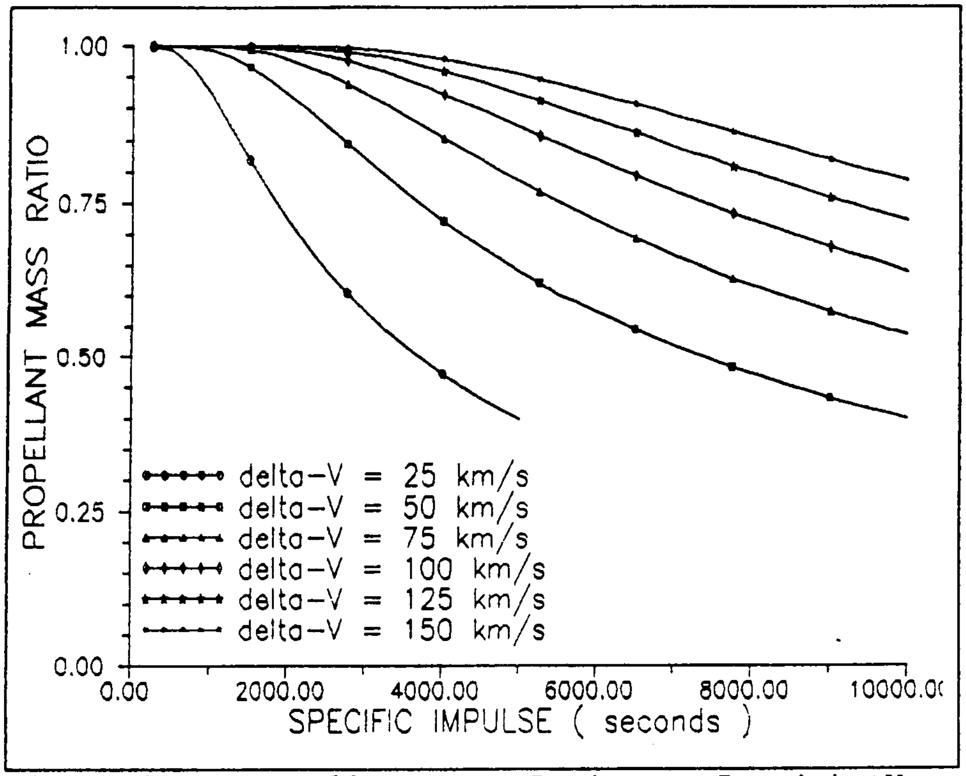


Figure 3.1: Propellant Mass Ratio vs. I_{sp} with ΔV as a Parameter

$$\frac{m_l}{m_o} = e^{-\frac{\Delta V}{I_{sp}g}} - \frac{(I_{sp}g)^2}{2\alpha t_{pr}}(1 - e^{-\frac{\Delta V}{I_{sp}g}}) \qquad (3.4)$$

where α is the specific power of the propulsion system and t_{pr} is the burn time. This equation has been graphed for several values of ΔV and αt_{pr}, two of which are shown in Figures 3.2 and 3.3. The important fact obtained from these graphs is that there is an optimal I_{sp} that yields the highest payload mass ratio for given values of αt_{pr} and ΔV. This I_{sp} can be found by taking the derivative of Equation 3.4 and setting it equal to zero, which yields

$$\left(\frac{2\Delta V\alpha t_{pr} + 2I_{sp}^3 g^3 + \Delta V I_{sp}^2 g^2}{2\alpha t_{pr} I_{sp}^2 g}\right)e^{-\frac{\Delta V}{I_{sp} g}} - \frac{g^2 I_{sp}}{\alpha t_{pr}} = 0. \qquad (3.5)$$

This equation must be solved by iteration with known values of burn time and ΔV. Thus, in order to obtain the highest payload mass ratio possible for a given mission, the engine should be able to operate at or near this optimal I_{sp}.

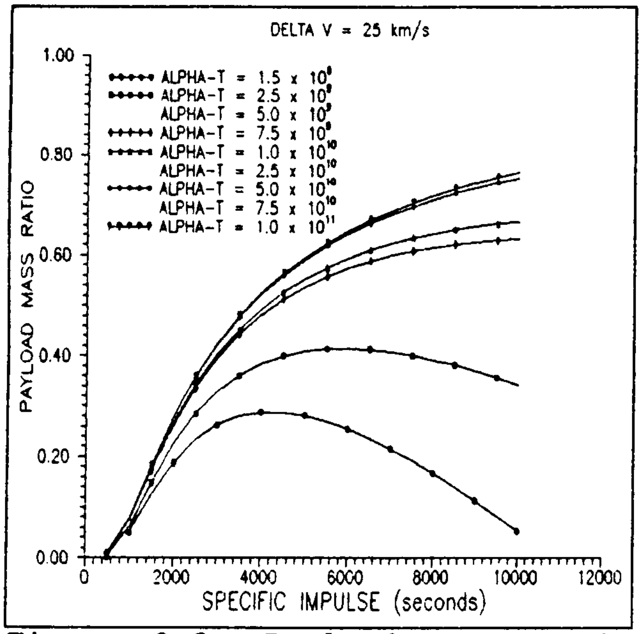


Figure 3.2: Payload Mass Ratio for ΔV = 25 km/s

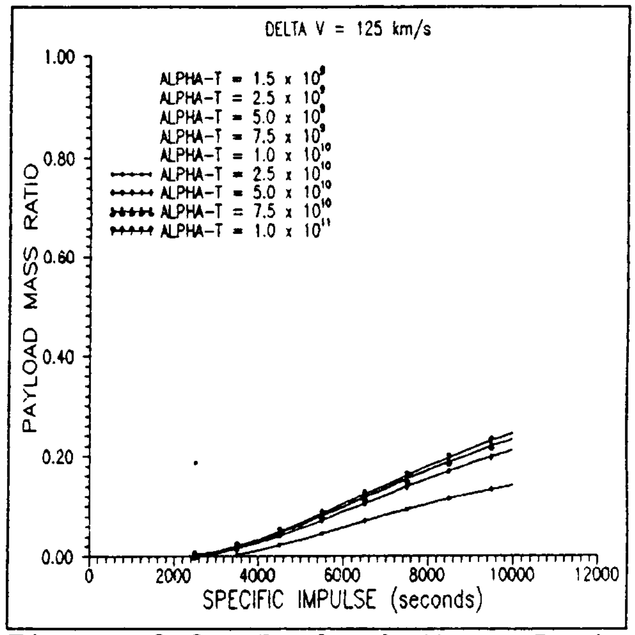


Figure 3.3: Payload Mass Ratio for ΔV = 125 km/s

An important parameter slightly different from the specific power of the propulsion system, α, is specific propulsion power, α_0. Whereas α was defined as the power output of the propulsion system over its mass, α_0 is defined as the power output of the propulsion over the initial mass of the spacecraft, m_0, or

$$\alpha_o = \frac{W}{m_o}. \tag{3.6}$$

Using the definition of the propulsive power

$$W = \dot{m}_p \frac{V_{ex}^2}{2} \tag{3.7}$$

and Equations 3.2 and 3.3, the specific propulsion power can be written as

$$\alpha_o = \frac{(I_{sp}g)^2}{2t_{pr}}\left(1 - e^{\frac{-\Delta V}{I_{sp}g}}\right). \tag{3.8}$$

This equation establishes that a_0 is a function of I_{sp}, ΔV, and burn time, and it is graphed in Figure 3.4 for a ΔV of 50 km/s (a typical value for the acceleration from the nominal orbit to a remote planet). Thus, the propulsive power required for a mission (ΔV, I_{sp}, and t_{pr}) can be found by multiplying Equation 3.8 by the initial mass of the station. An upper bound on the specific propulsive power required can be found by setting the term corresponding to the propellant mass ratio in Equation 3.8 equal to unity. The resulting equation is

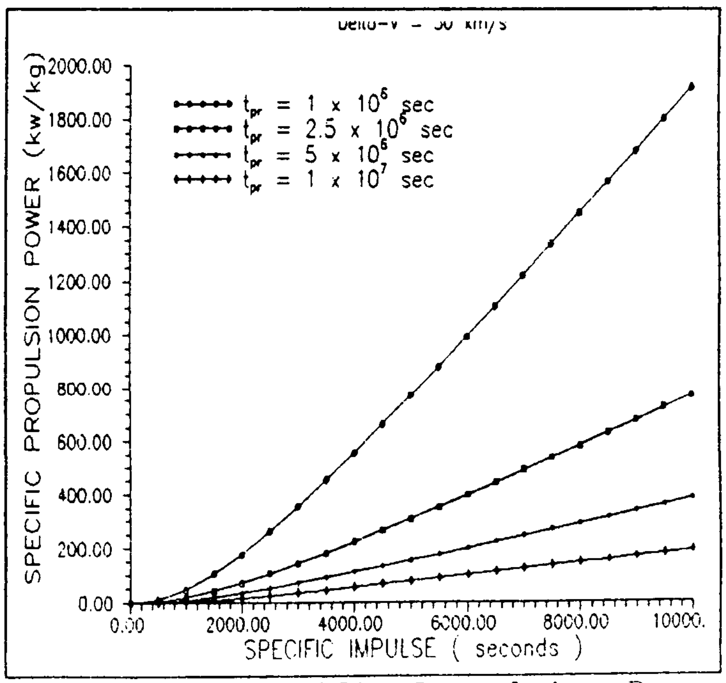


Figure 3.4: Specific Propulsive Power vs. I_{sp} with t_{pr} as a Parameter

$$\alpha_{o,max} = \frac{(I_{sp}g)^2}{2t_{pr}} \qquad (3.9)$$

and this equation allows an upper α_0 to be approximated from estimates of the I_{sp} and burn time for the mission.

Two other equations that will be useful in the analysis of the different propulsion systems considered are the total initial mass of the station and the impulse required. These equations are

$$m_o = m_{payload} e^{\frac{\Delta V}{I_{sp}g}} \qquad (3.10)$$

where $m_{payload}$ is defined to be the total dry mass (including the propulsion system) of the station and

$$J = m_p I_{sp} g. \qquad (3.11)$$

Equation 3.11 is where the practical effects of the I_{sp} manifest themselves and is shown in Figure 3.5 as impulse vs. I_{sp} with ΔV as a parameter. The dramatic rise in impulse required as the I_{sp} is lowered can be clearly seen as well as the rise in impulse required as the ΔV is increased. This figure gives insight into two important considerations for a propulsion system, the two components of impulse, thrust produced and thrust time. The thrust vs. time curves are shown in Figure 3.6 for different impulses, and from these curves, trade-offs between thrust and burn time can be performed for an impulse given by Equation 3.11. For example, at an I_{sp} of 5000 seconds and payload mass of 1×10^8 kg, an impulse of about 1×10^{12} Ns is required for a ΔV of 50 km/s. With an I_{sp} of 500 seconds, a ten-fold decrease from before, the impulse required

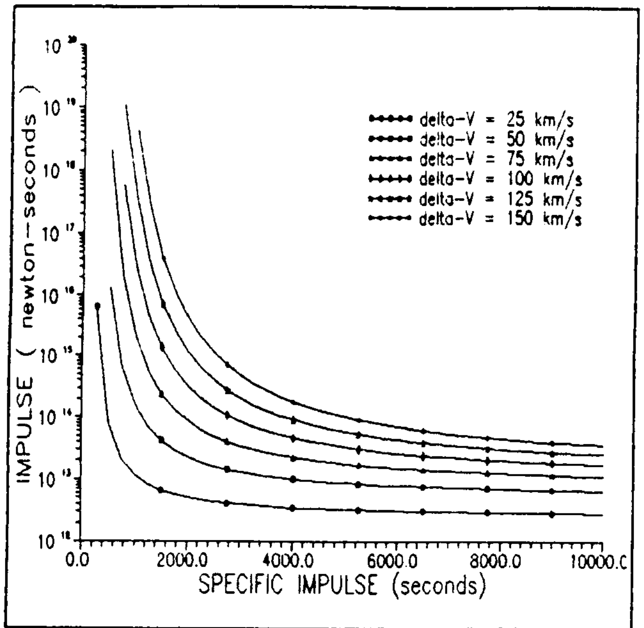


Figure 3.5: Impulse vs. I_{sp} with ΔV as a Parameter (Payload Mass = 1×10^8 kg)

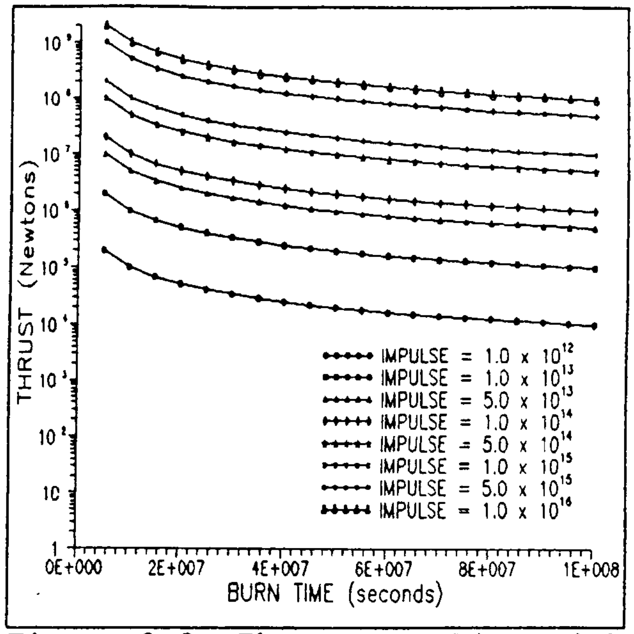


Figure 3.6: Thrust vs. Time with Impulse as a Parameter

for the same ΔV is about 1×10^{16} Ns, a ten thousand- fold increase. This increase in impulse would lead to a considerable increase in thrust levels and thrust time, both undesirable results from mass and engine lifetime viewpoints. From this point of view, it is beneficial to keep ΔV low while keeping the I_{sp} high.

The above discussion and equations have been an attempt to develop some fundamental relationships between the design parameters, mission requirements, and the physical nature of propulsion. With these equations, a method of systematically analyzing propulsion systems on a general level was developed. This preliminary method consisted of determining the impulse required for the most demanding mission the Emerald City would be required to accomplish. Representative values for I_{sp} , thrust, and lifetime of the propulsion system being considered were then used in order to ascertain whether the mission was possible with this system. Systems that were not close to generating the required impulse for the mission could be immediately discarded as a candidate for the main propulsion of the Emerald City.

A list of the more important results obtained from the theoretical investigation of the equations of propulsion are listed in Table 3.2. It should be kept in mind that these standards are developed from the propulsion system perspective only, and that other systems could present contradictory requirements which will invariably effect the final choice for propulsion.

Table 3.2: Major Points Obtained from Theoretical Analysis

1) The specific impulse, I_{sp}, should be optimized in order to increase the payload mass ratio and reduce the impulse required for attaining the necessary ΔV.

2) The actual payload mass should be minimized to keep the initial mass of the station reduced. This, in turn, keeps the impulse required reduced.

3) The ΔV required for a mission should be kept as low as possible in order to decrease impulse and minimize propellant mass ratios. This should be done by using more efficient transfers and planetary fly-bys when possible.

4) The thrust level and thrust time will be tailored to the impulse requirements given by Equation 3.11. They will be a design trade-off when choosing a propulsion system, considering its thrust output, lifetime, etc...

3.3 GENERAL LEVEL PROPULSION STUDIES

Before the analysis of different propulsion systems was initiated, important design parameters were identified that would be helpful in the comparison of different systems. Some of these parameters have been mentioned previously in while all of them are listed in Table 3.3. Whenever values for these parameters were attainable, they were used as a comparison of the different propulsion system considered for Project WISH.

Table 3.3: Important Design Parameters

Design Parameter	Significance
1) Specific Impulse (seconds)	Impulse per unit weight propellant
2) Specific Thrust (Newtons/kilogram)	Thrust per unit mass of engine
3) Specific Power (Watts/kilogram)	Power generated per unit mass of engine
4) Specific Propulsive Power (Watts/kilogram)	Power generated per unit mass of the initial ship
5) Total Impulse (Newton*seconds)	Thrust multiplied by engine life

With the information in Table 3.3 and the background presented in the theoretical section, the search for a propulsion system could begin. There were four basic classes of rocket engines that were considered for this application. These classes were chemical, electrical, nuclear fission/fusion, and antimatter.

3.3.1 Chemical

Chemical propulsion is the most common form of propulsion found today. The standard chemical engine creates a heated gas by some form of chemical reaction occurring in its combustion chamber. This gas then has its thermal energy converted into kinetic energy by a convergent-divergent nozzle and is exhausted.

Chemical propulsion has several advantages in its use. One of these advantages is that it can produce extremely high thrust levels, on the order of 1.0×10^6 N or better. It also is reliable and thoroughly flight-tested due to the number of missions it has flown. There are several different chemical systems and a tremendous amount of empirical data available, allowing the selection of the system that would meet more specific mission requirements.

However, all of these positive factors are offset by one glaring negative factor. This is the inherently low I_{sp} of the chemical engines, limited by the reaction energy released from the chemical reactants. The I_{sp} of chemical rockets are on the order of 450 seconds for the standard LH_2/LO_2 fuel and 600-700 seconds for more exotic fuels. This I_{sp} is too low for the missions required of the Emerald City, as demonstrated by the following example. It was found that for a typical scenario ΔV of 50 km/s and a payload mass of 1×10^8 kg, a propulsion system using the Space Shuttle Main Engine (I_{sp} = 453 seconds, T = 1.044×10^6 N)[3] would be required to generate an impulse of 3.42×10^{16} Ns. This corresponds to the equivalent of 1039 shuttle engines thrusting for one year, clearly an impractical case. For this reason, chemical engines were deemed impractical for application in Project WISH as the main propulsion system.

3.3.2 Electrical

Electrical propulsion was examined in three main subclasses, electrostatic, electrothermal, and electromagnetic. Electrostatic propulsion uses an electrical field to accelerate charged particles and exhaust them at extremely high speeds. Electrothermal propulsion passes a current through a resistive element to generate heat. This is then used to heat a gas which is expanded to high speeds and exhausted. Electromagnetic propulsion generates a magnetic field which is then used to accelerate particles to high speeds. These particles are then exhausted to produce thrust.

Electrostatic (ion) propulsion has one main benefit over chemical propulsion, a higher I_{sp}. Ion engines can have I_{sp}'s from 2000 seconds to 10000 seconds and beyond. This I_{sp} is much better suited for missions of the scope of Project WISH, as was demonstrated in the theoretical analysis. However, the main drawback of ion propulsion is the extremely low thrust levels and densities attained, on the order of a couple hundred millinewtons. This is much too low to generate the impulse demanded from Equation 3.11 and Figure 3.5 for accelerating the Emerald City to the required ΔV. Ion thrusters are also very complex and use fuels such as mercury or xenon that would be difficult to replenish in space. For these reasons, ion propulsion was not further considered as a viable alternative for the main propulsion system.

Electrothermal propulsion, otherwise known as resistojets or arcjets, is usually used for station-keeping or orbit adjustments due to its low thrust levels, on the order of a couple newtons. This low thrust made it impossible to generate the required impulse, thus it was not seriously considered as a main propulsion system for Project WISH.

Electromagnetic propulsion is represented by the magneto-plasma-dynamic (MPD) thruster. The current MPD thruster configurations have higher thrust levels than ion propulsion, on the order of a couple of hundred newtons, and a better I_{sp} than chemical, on the order of 2000-3000 seconds and upwards. With these figures, MPD thrusters deserve a serious look as an interplanetary propulsion system. However, due to the enormous mass of the Emerald City and the design objective aimed at keeping the free-flight time of transfers as long as possible, it was felt that MPD's were not the best choice for the main propulsion system of Project WISH.

3.3.3 Nuclear

This form of propulsion usually consists of a nuclear reactor that is used to heat a propellant which is exhausted or lasers used to start a fusion reaction in a material that becomes a plasma which is exhausted. Nuclear propulsion offers potentially high thrust levels at a reasonable I_{sp}, with thrusts on the order of kilonewtons and I_{sp}'s in the 850-5000 second range. The energy produced per unit mass of fuel in the nuclear reactions is second only to the antimatter reactions, which makes it an attractive source of power. Also, nuclear propulsion offers the opportunity to share the power generating and conditioning equipment with the Emerald City's power system, which is to be some form of nuclear reactor (see Chapter 7). Disadvantages of nuclear propulsion are the problem of human contamination and shielding, obtaining the required fuels for the nuclear reaction, and the fact that nuclear propulsion still requires some advances in technology. However, it is felt that these problems can be dealt with in a satisfactory manner during the course of this project. Therefore, nuclear propulsion was considered a propulsion system deserving further attention for Project WISH.

3.3.4 Antimatter

Antimatter propulsion obtains its energy from the reaction of matter with antimatter. The release of energy for such a reaction is enormous, and this energy goes to heating a fluid such as hydrogen for expansion and exhaustion. Antimatter propulsion has been envisioned producing thrust levels of meganewtons at a high I_{sp}. However, antimatter propulsion is still in the theoretical stage, with problems being encountered in the production, storage, and conversion of energy to thrust with an antimatter system. In spite of these drawbacks, antimatter offers enormous potential as a propulsion system for missions with high thrust, high I_{sp} requirements like Project WISH, and it was considered further as a potential main propulsion system.

3.4 DETAILED LEVEL PROPULSION STUDIES

The two systems that were studied in detail as the main propulsion system of Project WISH were nuclear and antimatter. The results of these studies are presented herein.

3.4.1 Nuclear Propulsion

To achieve interplanetary space travel within the required time constraints it is necessary to have high specific impulse and high thrust. It has been shown that I_{sp} values much greater than 1000 seconds will be necessary, which can be obtained from several types of nuclear systems. Another favorable feature of nuclear propulsion is the possibility of utilizing shared power/propulsion systems. This can be done by either having the propulsion system supplement the power generation from the thermal energy that is produced by the propulsion reactor, or by at least having both systems use the same fuel or processing subsystems.

Nuclear forms of propulsion are divided into fission and fusion type systems. These range in I_{sp} values from ~800 seconds for some fission systems, on up to ~1×10^6 seconds for some advanced fusion concepts. Several of the more viable nuclear propulsion systems were considered in each category with the intention that the most practical and suitable system for the station would be chosen from among these when more exact figures become available. The fuel and sources of fuel and propellant also had to be considered since these are critical substances for nuclear propulsion systems and the Emerald City is to use extraterrestrial resources.

Fission Systems

The types of fission nuclear propulsion systems under consideration fall into two categories: solid core and particle bed. Solid core reactors that have been designed for propulsion are the NERVA (Nuclear Energy Rocket Vehicle Application) and the SNRE (Small Nuclear Rocket Engine). The particle bed reactors are classified as Fixed Bed Reactors (FBR) and Rotating Fluidized Bed Reactors (RBR).

Solid Core

The NERVA and SNRE reactor cores consist of clusters of 3/4 inch hexagonal solid UC2-graphite fuel elements containing holes for the hydrogen coolant flow. The NERVA core uses single layered fuel beads in the elements. The NERVA is especially favored for use since the design was approaching flight-rated status when the nuclear propulsion program was terminated in 1973. Full design powers and temperatures were achieved on several occasions. Some design conditions and features of the NERVA and SNRE rocket reactors are shown in Table 3.4[4].

Table 3.4: Solid Core Reactor Data

	NERVA-1A	SNRE
Core Power, MW (thermal)	1500	370
Core Temp, K	2360	2550
Thrust, kN	333	73
Specific Impulse, sec.	825	875
Number of fuel elements	1878	564
Fuel	UC	UC ZrC-C
Total Engine Mass, kg	10400	2600

Fixed Particle Bed Reactor

Particle bed reactors use small pellets of fully enriched uranium-carbide in the range of 100 to 500 microns in diameter. In fixed bed reactors the fuel particles are held between two porous frits in an annular bed and are directly cooled by the working stream of propellant gas (see Figure 3.7[5]). Either a closed Brayton cycle is used with heli-

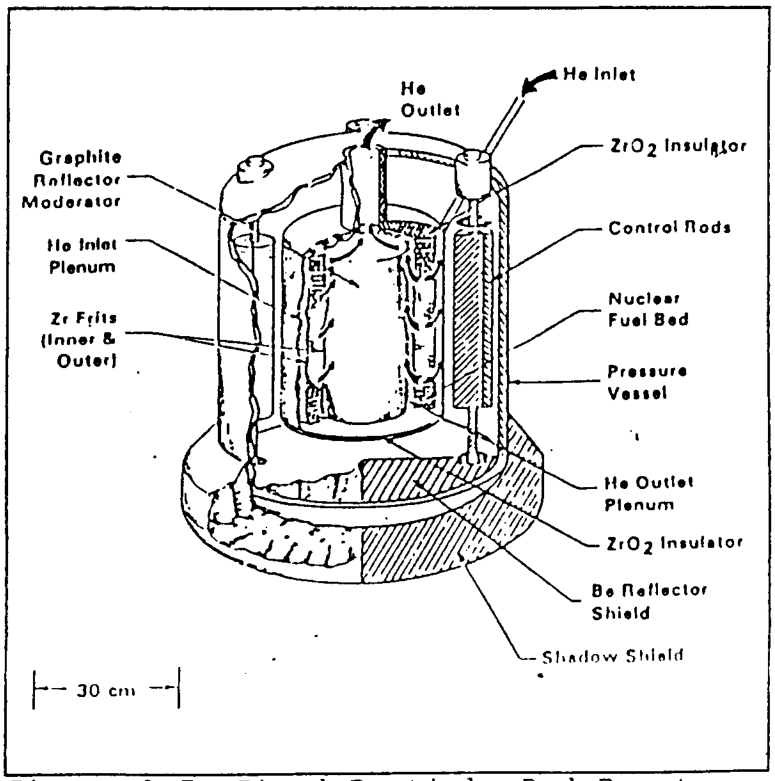


Figure 3.7: Fixed Particle Bed Reactor

um as the working gas or an open-cycle mode using hydrogen. The fuel bed thickness is usually on the order of 3 to 6 cm. The Fixed Bed Reactor has two main advantages for space applications. First, the very high power densities within the fuel minimize size and weight of the reactor. Secondly, the small temperature gradients produce minimal thermal shock and fatigue problems allowing fast start/stop operation. Specific impulse levels of over 1000 seconds appear feasible for FBR's.

Rotating Fluidized Bed Reactors

The RBR uses fine fuel particles also, but they are supported against the inside of a spinning porous drum, or frit, by the rotational forces as can be seen in Figure 3.8[6]. The small particle size gives a high surface-to-volume ratio, good heat transfer rates and high power densities within the core. This approach minimizes the temperature difference between the nuclear fuel and the coolant stream and the centrifugal forces on the rotating bed prevent loss of fuel particles even at high gas flow rates. An example based on calculations and some experimental data obtained at Brookhaven National Laboratory show that an RBR rocket engine utilizing uranium 233 fuel could develop a thrust of 90 kN and

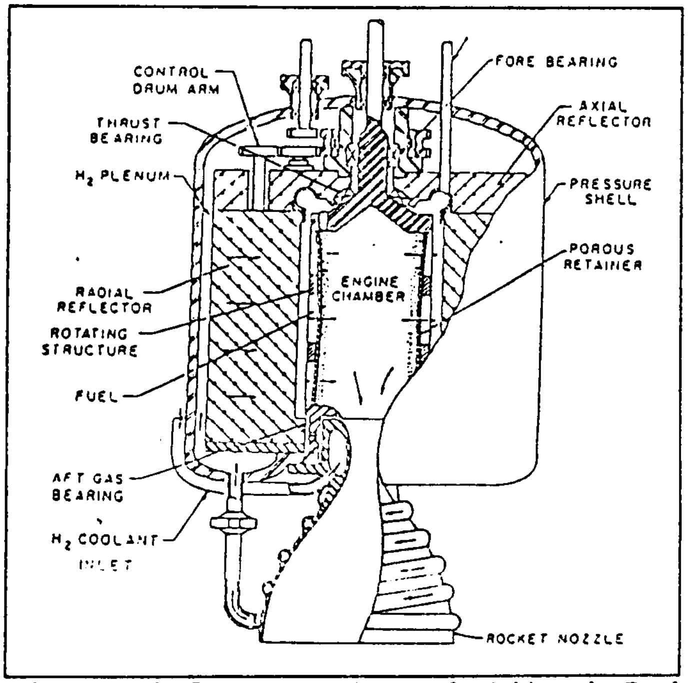


Figure 3.8: Rotating Fluidized Bed Reactor

have a specific impulse of 835 seconds with a thrust-to-weight ratio of 65 N/kg. Specific impulses in the range of 1000-1200 seconds for RBR rocket engines appear possible without any problems.

Fission Fuels

Fission reactors all use some form of uranium enriched fuels. Either uranium 233, uranium 235, or some uranium compounds such as uranium-carbide are necessary to provide the fission reaction. This could be a problem from the standpoint of storage, handling and processing in deep space missions. It has not yet been determined by the propulsion team whether there are extraterrestrial sources of uranium or uranium ore and thus fission fuel factor can not yet be incorporated into the decision making process regarding fission nuclear propulsion for the station.

Fusion Systems

The large amount of energy that is released per unit mass of fuel in a fusion reaction provides extremely high specific impulses. Additionally, fusion systems are capable of continuous operation at high thrust and specific impulse levels and this is what is needed for interplanetary travel within acceptable time periods. High power lasers (on the order of 10 MJ) are needed to ignite the fuel creating the fusion reaction, thus there is a need for a system to power the lasers and additional weight. Since the fuel has to be heated to extremely high temperatures to turn it into a plasma, some form of confinement must be provided to allow for enough fusion reactions to take place.

Thus, the types of fusion nuclear propulsion systems under consideration fall into two main categories: inertial confinement (ICF) and magnetic confinement.

Two different systems were considered within each of the two types of confinement schemes. Inertial confinement types include the Propellant Surround Rocket and the Magnetically Insulated Inertial Confinement system (MICF). Under the category of magnetic confinement those considered were the Translating Compact Toroid (TCT) and the Field Reversed Confinement (FRC) propulsion systems. These are all discussed in further detail below.

Propellant Surround Rocket

This concept has the best propellant/plasma coupling with a high specific impulse (values up to 2500 seconds appear possible). It seems to offer the greatest promise of allowing heating of the propellant without the fusion reaction being quenched. As is shown in Figure 3.9[7], a ball of frozen hydrogen or other suitable propellant is placed around the target and high power laser light provides the pulsed energy.

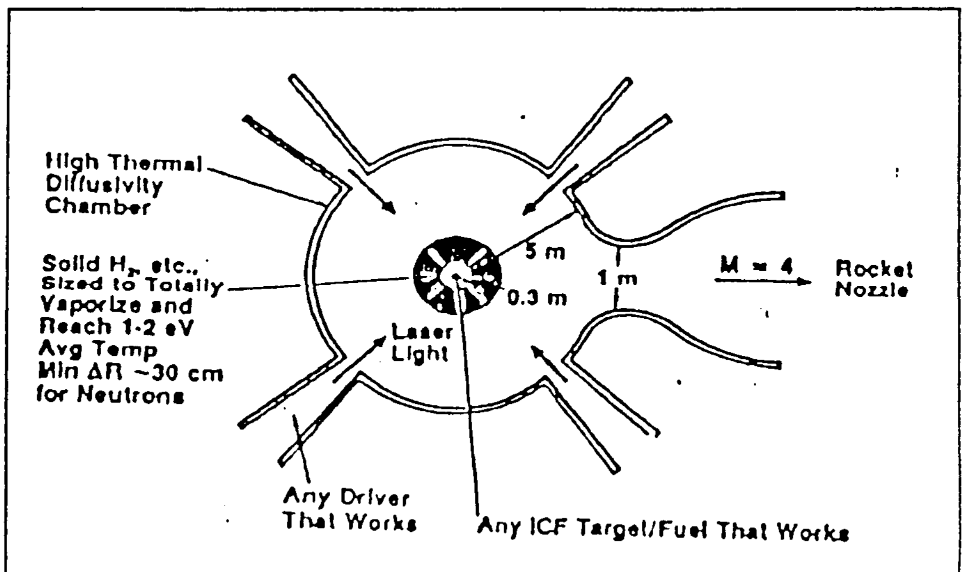
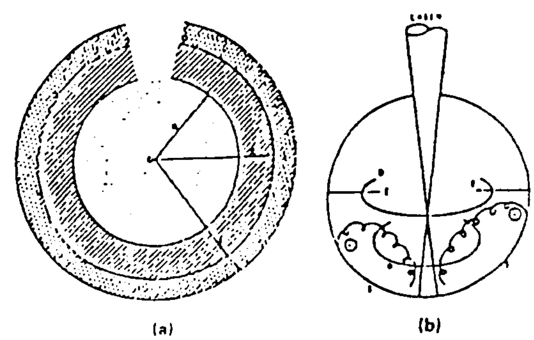


Figure 3.9: Propellant Surround Fusion Concept

Virtually all of the fusion energy is transferred to the hydrogen which then turns into a high pressure gas and expands out the nozzle. The major disadvantages of this type of system is the complexity of fabricating the frozen propellant surrounds and the fact that thrusting is pulsed. Along with most other nuclear fusion systems there is not much empirical data regarding this system.

Magnetically Insulated Inertial Confinement

In the MICF concept physical containment of the plasma in the target area is provided by a metallic shell, while its energy is insulated from the walls by a self-generated magnetic field (see Figure 3.10[8]). As in other forms of fusion propulsion a high-power laser provides the input energy to create the fusion reaction. A hot plasma is formed inside the spherical shell as a result of the bombardment on the inner surface by the intense laser beam. In addition to forming the plasma, the laser creates a toroidal magnetic field as a result of the current loop produced by the ejected hot electrons (see Figure 3.10b). This magnetic field rapidly expands through-out the inner region of the shell providing the insulation of the thermal energy from the surrounding walls of the chamber. A theoretical reference case for MICF was developed by T. Kammash and D.L.



Schematic diagram of (a) the reactor chamber and (b) process of magnetic field generation.

Figure 3.10: MICF Reactor Schematic

Galbraith[8] using 10.01 cm deuterium-tritium pellets for fuel with a tungsten metallic shell of 0.01 cm thickness surrounding the solid fuel. The results are found in Table 3.5 and show that thrust levels of 25,000 kN at a specific impulse of over 3000 seconds can theoretically be obtained from this type of system.

Table 3.5: MICF Reference Case

Fuel	: 10.01 cm DT pellets
Input laser energy	: 2.7 MJ
Exhaust Velocity	: 33,000 m/s
Specific Impulse	: 3300 seconds
Thrust	: 25,000 kN
Jet Power	: 1000 MW
Repetition rate	: 10 per second

Translating Compact Toroid

This is the first of the two fusion systems considered which utilize magnetic fuel confinement. In magnetic confinement the actual confinement is provided by an externally applied magnetic field. The TCT has the favorable characteristic of high power density and the pulsed thrusting should be much smoother than the Propellant Surround Rocket. The power supply and driver for the TCT appear to be more easily obtainable but propellant addition is a major problem. However, it is anticipated that a solution can be found to this problem during the next several decades. A possible configuration for the TCT is shown in Figure

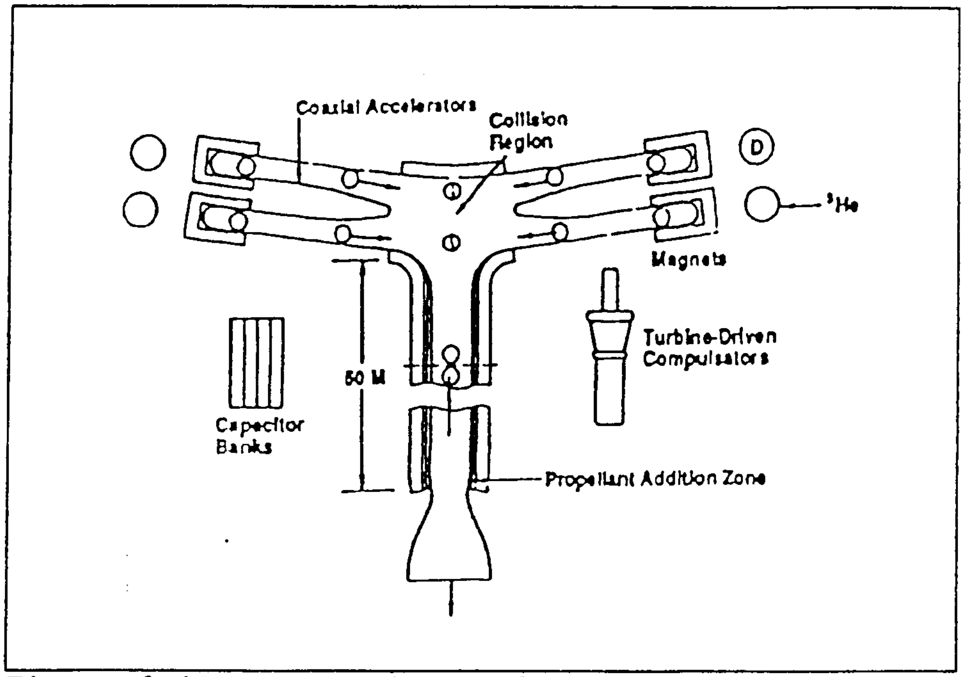


Figure 3.11: TCT Fusion Rocket Concept

3.11[9]. It uses coaxial accelerators that are angled slightly to allow a small perpendicular component of velocity after collision. This will provide translation into the propellant addition zone where the propellant is injected and becomes a plasma expanding through the nozzle to produce thrust. This system will require very high temperature materials but is slightly better overall than the Propellant Surround Rocket. Some comparisons were made by V. Haloulakos between this type of fusion system, a fission system and RL-10 cryogenic engines for a sample LEO to GEO mission and the data looks promising. This information is summarized in Table 3.6[10].

Field Reversed Confinement

The FRC type system has the advantages of good confinement, high beta particle characteristics, high power densities and a compact design. Several experiments are currently in progress world wide but progress lacks that of other fusion systems. Thrust is achieved through the use of a magnetic nozzle as is shown in Figure 3.12[11]. The plasma

Table 3.6: Space Transfer Vehicle Design Data

Space Transfer Vehicle Design Data

LEO to GEO Mission Data: Payload Mass 36,000 kg Velocity Increment: 4,500 m/s				
	Cryogenic	Fission	Fusion (TCT)	
Engine	RL-10	ALPHA	New	New
Thrust (KN.)	66.7	71.7	100	1,000
Specific Impulse (s)	450	860	2,300	1,000
Mass Breakdown				
Propellants (kg)	68,712	30,877	10,849	54,858
Fuel (LH_2)	10,571			
Oxidizer (LO_2)	58,141			
Propellant Tanks				
Tot. Volume (m^3)	200	495	174	879
Mass (kg)	1,681	3,324	1,168	5,905
Pressurization				
(He system) (kg)	283	560	197	995
Engine (kg)	132	2,567	11,282	49,050
Miscellaneous (kg)	703	1,390	488	2,470
Total vehicle mass (kg)	107,512	74,719	59,984	149,279

escaping the closed magnetic field region is mixed with the propellant as it is injected along the open magnetic field lines. This allows a long path length for good fuel--propellant mixing. The mixture is then exhausted through the magnetic nozzle producing thrust. The open field lines of this configuration make the

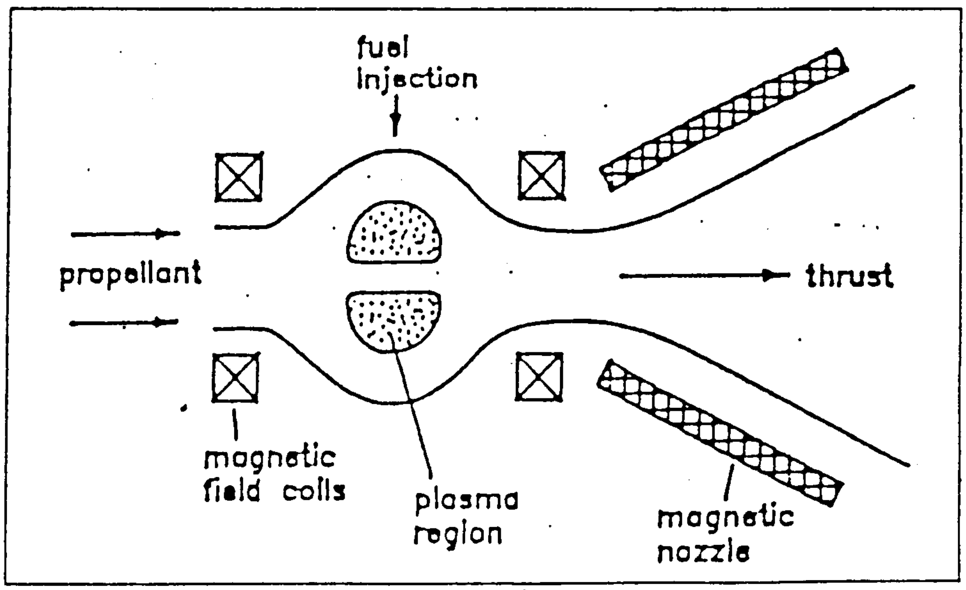


Figure 3.12: FRC Fusion Rocket Concept

use of the magnetic nozzle attractive and the temperature of the exhaust gas is not materials limited because the gas does not come in contact with the actual nozzle. The FRC propulsion system boasts steady-state operation at specific impulses from 10^6 to 10^3 seconds with thrust levels from 0.4 to 50 kN. For example, at a power level of 0.5 GW, the addition of 0.5 kg/s of propellant to 5.2×10^{-7} kg/s of plasma gives an I_{sp} of 5000 seconds and a thrust level of 9 kN.

Fusion Fuels

Although there are many possible fusion fuels that can be considered, most are immediately eliminated because they would produce almost no power. Some also produce neutrons which are very energetic and will readily penetrate materials increasing the need for shielding. The fuel with the greatest power density is deuterium-tritium. D-T is 10 times more powerful than any other fusion fuel available but it also produces neutrons and has a radioactive reactant. In addition, tritium would be difficult to obtain in space and has a half-life of 12.3 years. Deuterium-Helium (D-^{3}He) is a very energetic reaction also, having a specific energy of 3.5×10^{14} J/kg, which is second only to the proton--antiproton annihilation (9×10^{18} J/kg). There are also large extraterrestrial sources of helium that have been identified in the solar system, as is seen in Table 3.7[12], making it more likely that fuel could be replenished in space. The fine regolith of the lunar surface itself has over 1 million metric tons of ^{3}He which was deposited by the solar wind. This source could provide over 107 GW·yr of electric power. Because of these facts it appears that deuterium-helium would be the best choice for any fusion system. Deuterium could be processed from hydrogen, which would also be used as a propellant and is also available in abundant amounts in the solar system.

Table 3.7: Extra Terrestrial Sources of ^3He

Sample	^3He Content (g/g)	^3He Potential (kg)
solar wind	1.4×10^5 ion/m^3	3 x 107 ion/m^2s
lunar surface	37	1.1×10^9
Jupiter	$2.2 - 3.5 \times 10^5$	7×10^{22}
Saturn	$2.2 - 3.5 \times 10^5$	2×10^{22}
Uranus/Saturn	(atmospheric)	$\sim 10^{22}$

3.4.2 Antimatter Propulsion

Antimatter propulsion is a high thrust, high I_{sp} propulsion system based on the annihilation of antiprotons with protons. This reaction between the two particles converts the entire rest mass of the particles into energy, which is then used to heat a propellant that is expanded to high exit velocities.

A typical scenario envisioned for the application of antimatter propulsion is manufacturing the antimatter in the form of antihydrogen by specialized antimatter factories either on Earth or the moon. This antihydrogen, consisting of an antiproton and an antielectron (positron), is formed into balls of ice that are transferred by high vacuum cryogenic containers to the using vehicle's specially designed fuel tanks. When energy is needed for propulsion, the antiprotons are extracted from the antihydrogen by using strong electric and magnetic fields and collided with protons releasing their energy. This energy is given by the formula $E = mc^2$, and, since the entire rest mass of the two particles is converted into energy, the reaction yields 9.0×10^{16} J/kg for use in propulsive thrust. The energy generated is then used to heat a fluid such as hydrogen to high temperatures which is then expanded and exits the engine at high exhaust velocities.

Matter/Antimatter Reaction

Figure 3.13 shows schematically the reaction of protons and antiprotons in a rocket engine. The reaction first produces anywhere between 3 to 7 charged and neutral pions, where the average is 3.0 charged pions and 1.5 neutral pions[13]. These pions are unstable and convert into gamma rays for the neutral pions and muons for the charged pions. Before they decay however, they have travelled 21 meters, far enough that the pions should be able to be directed by a magnetic field into a flow used for thrust or heating of propellant. The muons that are the result of the pion decay are also energetic particles and can be used for obtaining additional thrusts.

Theoretically, antimatter propulsion is a conceivable method for obtaining thrust. There are, however, several technical problems that will have to be resolved in order to utilize the tremendous energy that is generated from the matter/antimatter reaction. Forward[14] discusses several of these problems and offers theoretical solutions to many of them. Three of the principal problems that will be discussed here are

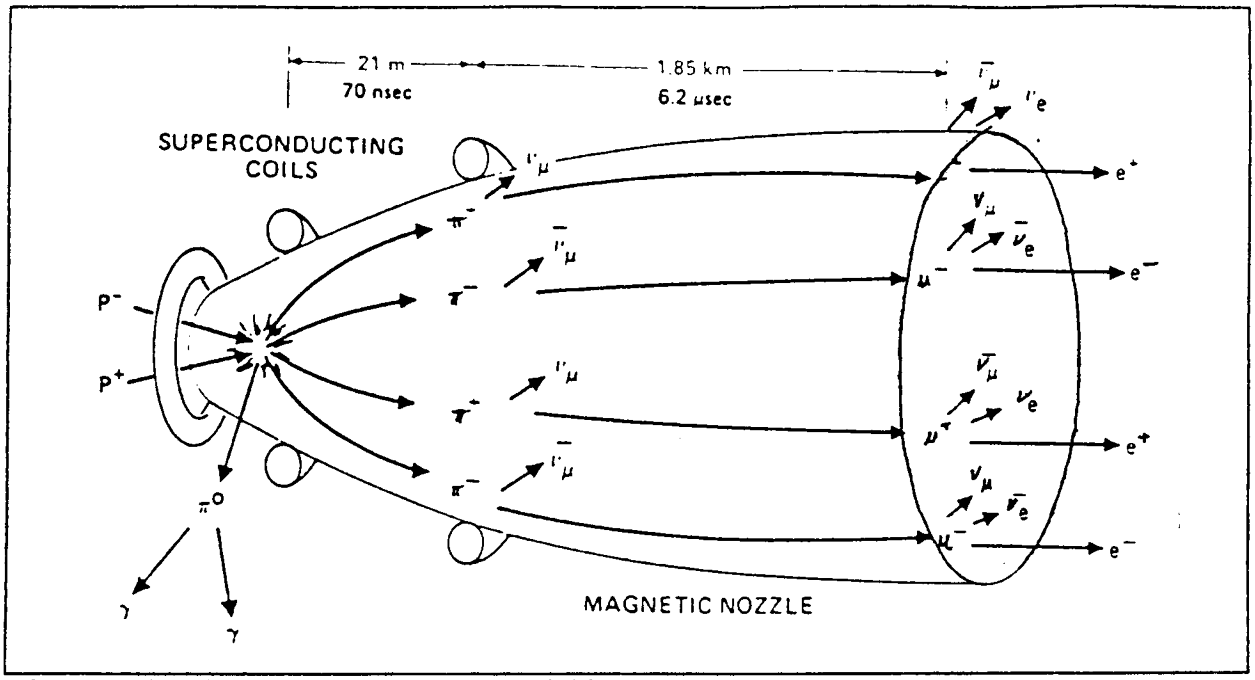


Figure 3.13: Antimatter Annihilation

the production of antiprotons, the confinement of antimatter, and the conversion of the reaction energy into propulsive force.

Production of Antiprotons

Antiprotons are created by sending a beam of high-energy protons into a dense target made up of tungsten or other heavy nuclei atoms. When the protons strike a dense nuclei, the enormous kinetic energy of the relativistic proton is converted into a spray of particles, some of which are antiprotons. A magnetic field focuser and selector is used first to segregate the antiprotons from the other particles and then to direct the antiprotons into a storage ring. These antiprotons have a wide spread of energies and thus need to be "cooled" to the same energy level in order to facilitate deceleration to subrelavistic velocities for storage.

Since the discovery of the antiproton at Lawrence Berkeley Laboratory in 1955, the yearly production of antiprotons has been steadily climbing. As can be seen from Figure 3.14[15], the rate of antiproton production has increased by an order of magnitude about every 2.5 years. Continuing this trend into the future, by 2010, the yearly production of antiprotons will be on the order of 10^{23} antiprotons per year, about 167 mg of antimatter. However, one must keep in mind two facts that could lead to higher production rates in the future. The first one is that the extrapolated curve shown in Figure 3.14 is a conservative estimate, with almost all of the actual numbers falling above this line. Recent facilities such as the LEAR facility at CERN in Switzerland and the Fermilab antiproton facility in the United States fall above this line, as well as the projected facility at Los Alamos National Lab in the United States.

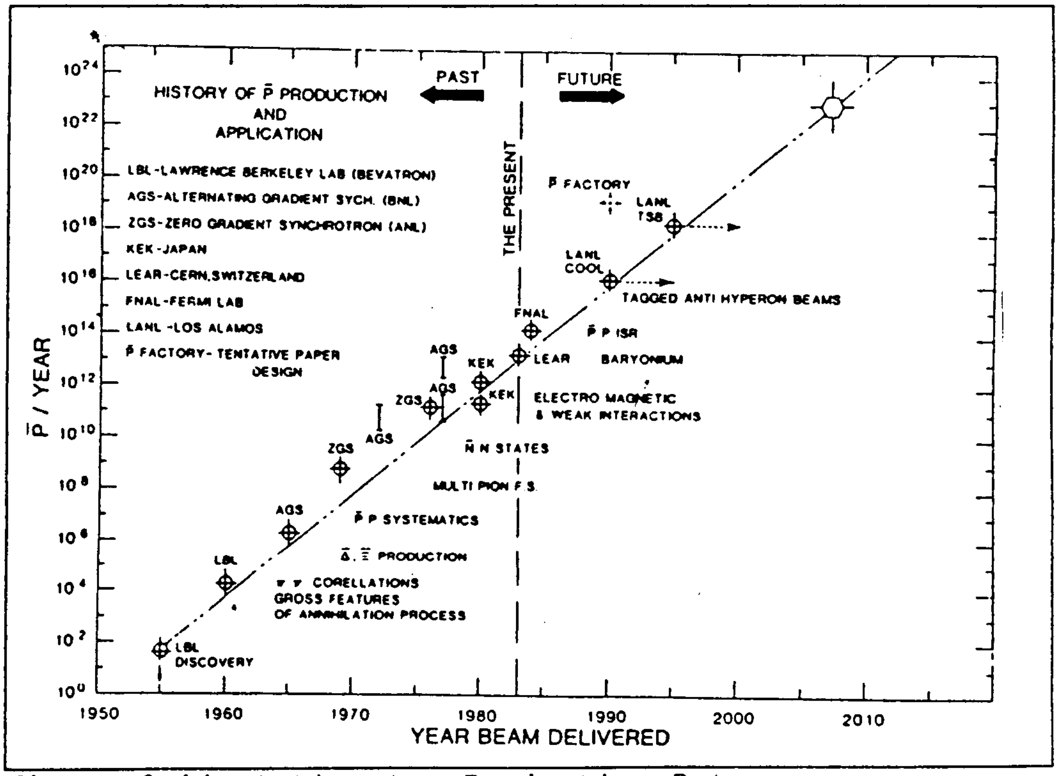


Figure 3.14: Antiproton Production Rate

The second fact that should be noted is that the antiprotons today are being produced in facilities geared towards the study of atomic physics, not towards the generation of antiprotons. Thus, they do not operate at optimum efficiencies for generating antiprotons. With a concentrated effort of research funding put into the generation of antiprotons, perhaps even a factory optimized for this task, the number of antiprotons produced per year should be sufficient for the production of kilograms of antihydrogen. Such a factory has been conceptualized by Forward[16] and is shown in Figure 3.15. In his conceptualization, several proton beams are used and the components are optimized for antiproton production.

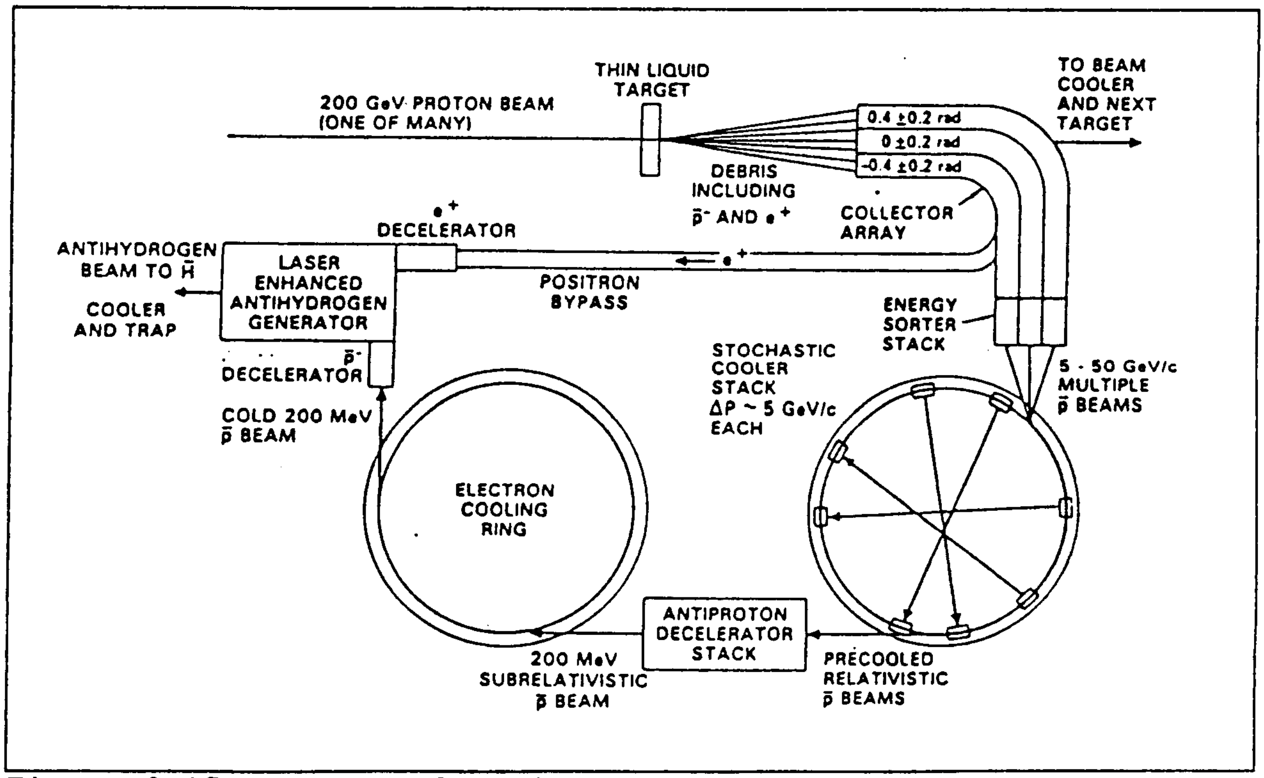


Figure 3.15: Conceptual Antiproton Factory

Confinement of Antimatter

The basic problem with the storage of antimatter is how to prevent it from coming into contact and reacting with the normal matter in its vicinity. The most obvious way is to electrically charge the walls of the confinement chamber in order to repel the charged antiproton. Ideas similar to this have been studied in-depth for normal matter ions, and this work can be directly applied to the problem of antiproton storage. Unfortunately, such "ion traps" are limited in both the number of ions storable and the duration in which they can be stored. These ion traps can function as an intermediary, a stepping stone for the study and development of more advanced concepts of antiproton confinement.

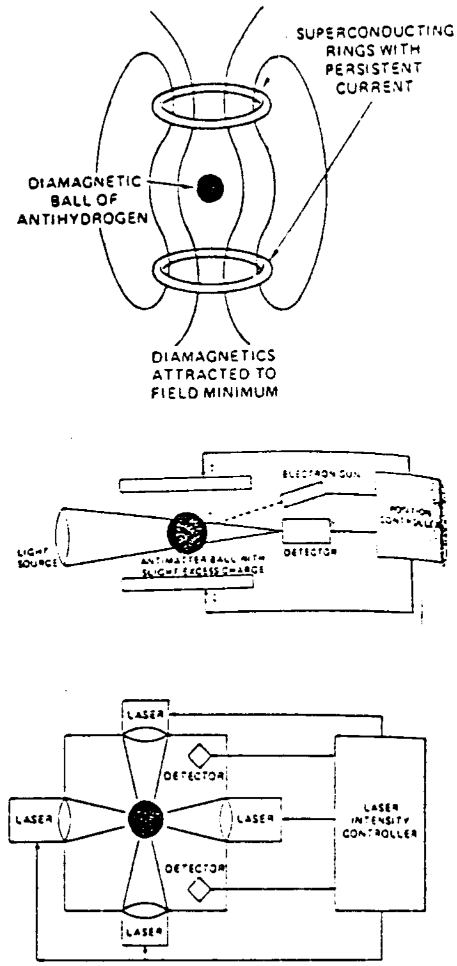


Figure 3.16: Antimatter Confinement Concepts

The storage of antihydrogen ice on board the using vehicle is also a problem that has been given consideration. Forward[17] details three methods of antimatter control that have been examined; magnetic levitation, electrostatic levitation, and laser levitation. In magnetic levitation, the diamagnetic properties of the antihydrogen molecule are used to control the antimatter in a magnetic field. In electrostatic control, electric fields are used to manipulate a slightly charged ball of antihydrogen and confine it. In laser levitation, the antimatter is supported by the light pressure of lasers surrounding the ball. Detectors feed information to the lasers as to what intensity is needed to keep the antimatter confined. These three containment concepts are shown in Figure 3.16.

Extracting Thrust From Reaction Energy

The energy released from the reaction of the protons and the antiprotons in the thrust chamber is tremendous. The problem is the effective transfer of this energy into a propellant for exhaustion. The energy can be transferred from the energetic pions and muons to the hydrogen molecules through a collision coupling system[18]. In this concept, the charged particles transfer their energy to the hydrogen, which then ionizes and is accelerated with a magnetic nozzle. Another method of energy transfer that has been mentioned is using a core of high-melting-point material such as tungsten to stop the annihilation products and transfer the heat to a propellant[19]. Cassenti[20] has shown that the maximum efficiency that an antimatter engine heating hydrogen as a propellant can have is 44 % with an efficiency of 40 % corresponding to an I_{sp} on the order of 12 x 10^6 seconds. It is obvious that an I_{sp} this high would be unnecessary for interplanetary applications so the efficiencies would not need to be this high.

Antimatter Engine Concepts

Two antimatter engine concepts will be discussed as representative figures for antimatter propulsion. These concepts are a high thrust annihilation engine discussed by Morgan[21] and a solid core thermal rocket based on NERVA technology discussed by Howe[22]. These concepts are shown in Figure 3.17 and 3.18 and in Table 3.8. It should be noted that Howe's concept is envisioned as a relatively near-term possibility that uses tested NERVA technology while Morgan's is more conceptual in nature.

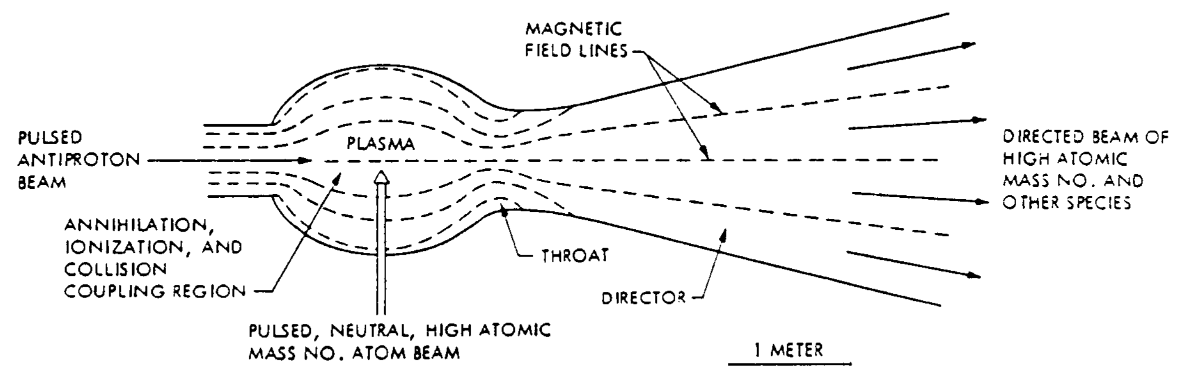


Figure 3.17: High-Thrust Annihilation Engine Concept

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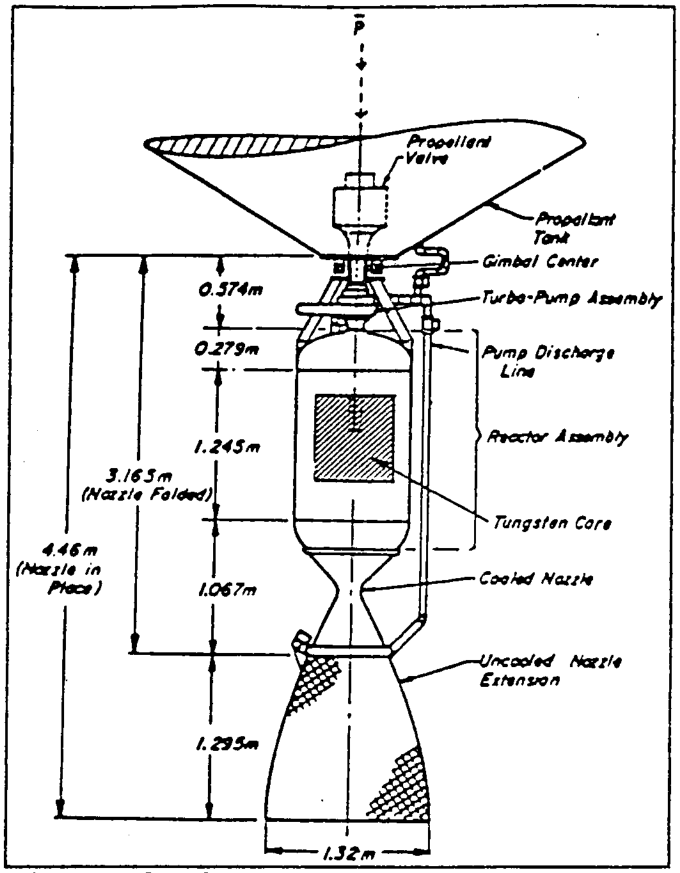

Figure 3.18: NERVA-Based Antimatter Engine Concept

Table 3.8: Data on Antimatter Engine Concepts

	HIGH-THRUST ANNIHILATION ENGINE	NERVA-BASED ENGINE
Thrust (Newtons)	5.5×10^5	4.4×10^5
Specific Impulse (sec)	14000	1100
p Flow Rate (μg/sec)	33	13
Power Level (MW)	----	2700
Engine Mass (kg)	----	11000

3.4.3 Comparison of Nuclear and Antimatter Propulsion Systems

After data had been accumulated on both nuclear and antimatter propulsion systems, a conclusion was made on which one would be the initial choice for Project WISH. Comparing the figures available, antimatter was chosen to propel the Emerald City. This choice was made on the basis of antimatter's higher projected thrust and I_{sp} and the results of the impulse analysis performed on the nuclear propulsion systems (see Table 3.9). The conclusions drawn from this analysis is that even the more promising fusion systems could not generate a sufficient impulse to perform the more demanding transfers that would be required for Project WISH. However, this conclusion was drawn assuming no in-flight propellant replenishing, thus the ΔV used was the combined value for the transfer from the nominal orbit to the destination and from the destination back to the nominal orbit. This decision was made because it was felt that the processing of hydrogen from the several different sources it would be attained from would be too difficult to accomplish on the Emerald City and that it would be limited to planets where hydrogen was present and extractable. More research should be done on the topic to determine whether or not this limitation is warranted. If it is decided that the ship could produce propellant away from its nominal orbit, then nuclear systems could be looked into with more justification for use.

Table 3.9: Comparison of High-Thrust Propulsion Systems

Total Delta-V = 140 km/s $m_{payload} = 1 \times 10^8$ kg

Outward Accel = 35 km/s
Outward Decel = 30 km/s
Return Decel = 40 km/s
Return Decel = 35 km/s

	CHEMICAL	NUCLEAR	ANTIMATTER
T (N)	1.044×10^6	1×10^5	5×10^5
I_{sp} (sec)	453	2300	8956
mass (kg)	3175	11282	11000
m_{01} (kg)	4.81×10^{21}	4.95×10^{10}	4.92×10^8
J_1 (Ns)	2.14×10^{25}	8.80×10^{14}	1.42×10^{13}
J_2 (Ns)	8.10×10^{21}	1.74×10^{14}	8.40×10^{12}
J_3 (Ns)	9.49×10^{18}	5.20×10^{13}	7.55×10^{12}
J_4 (Ns)	1.17×10^{15}	8.39×10^{12}	4.30×10^{12}
No. Engines	2×10^{11}	3400	11
Burn Time	3 years	1 month	1 month

3.4.4 Analysis of Antimatter Propulsion System

The antimatter propulsion system is analyzed in a slightly different manner than the standard systems looked into earlier. For the analysis presented here, it will be assumed that the optimum operating condition for the antimatter engine will be at the I_{sp} that minimizes the mass of the antimatter required. This condition would be most desirable for intermediate-term ventures such as Project WISH because it would lessen production and storage problems that would be encountered. Another assumption that was made is that the antimatter system expelled only heated hydrogen, no annihilation products were considered as part of the exhaust.

It has been shown[23] that in order for the antimatter mass to be minimized, the exit velocity should be given by

$$V_e = 0.6275 \Delta V \tag{3.12}$$

which corresponds to an I_{sp} of

$$I_{sp} = 0.06397 \Delta V. \tag{3.13}$$

Using Equations 3.3 and 3.11 and performing the algebra, the impulse required is given by

$$J = 2.4606 m_{payload} \Delta V. \tag{3.14}$$

The mass of antimatter, m_a, can be found by inserting Equation 3.12 into the original energy balance equation and is given by

$$m_a = \frac{0.386 m_{payload} \Delta V^2}{e c^2} \tag{3.15}$$

where ϵ is the efficiency of energy to thrust conversion and c is the speed of light (3×10^8 m/s). Both Equations 3.14 and 3.15 are graphed for mission values of $m_{payload}$ and ΔV and are shown in Figures 3.19 and 3.20. Using an estimated payload mass of 1×10^8 kg, a lifetime ΔV of about 650 km/s, and a energy-to-thrust conversion of 25 %, the mass of antimatter required would be around 30 kg, or about 10^{29} antiprotons.

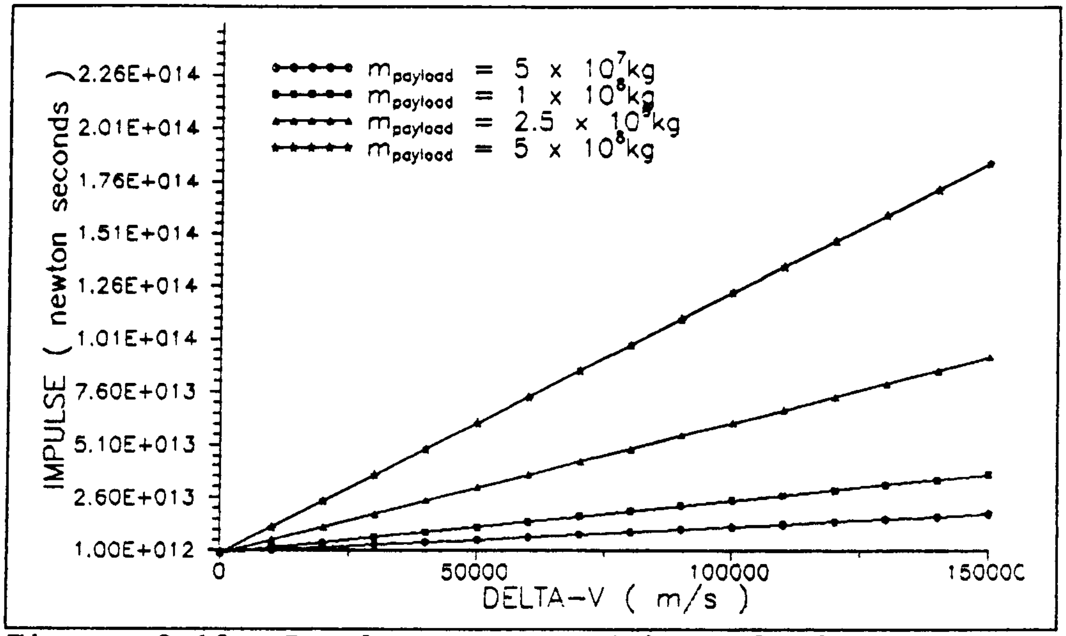

Figure 3.19: Impulse vs ΔV with Payload Mass as a Parameter for an Antimatter Engine Operating at Minimum Antimatter Mass Conditions

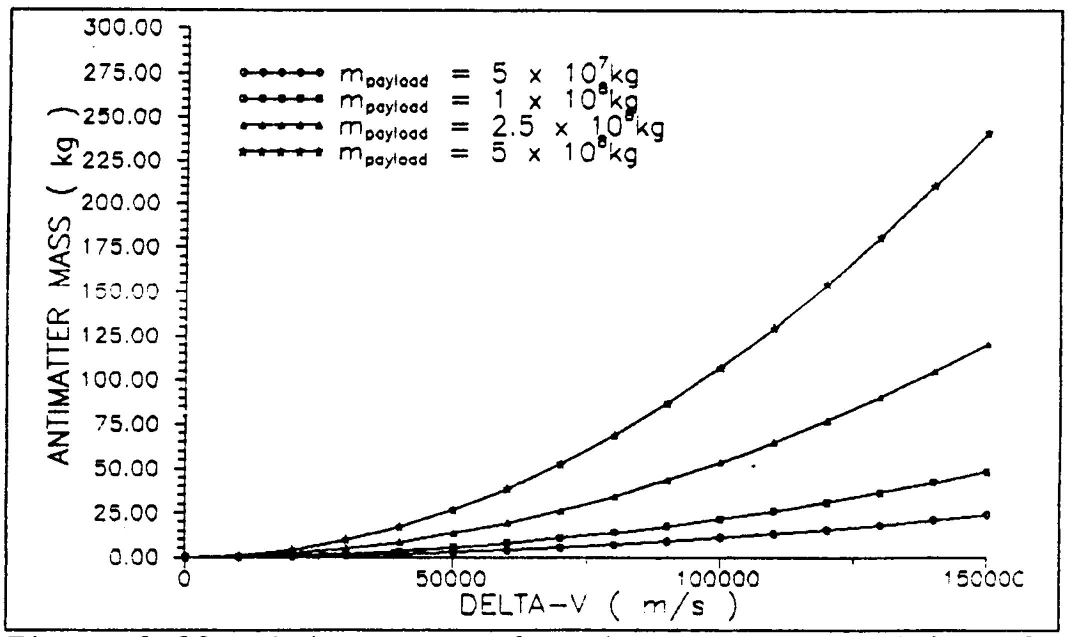

Figure 3.20: Minimum Mass of Antimatter vs. ΔV with Payload Mass as a Parameter

3.5 CONCLUSION AND FUTURE WORK

An antimatter propulsion system was chosen as the preliminary propulsion system for the Emerald City. This conclusion was based mainly on the fact that because the ΔV and mass payload were so large, an antimatter engine with its high thrust and high I_{sp} was the only feasible alternative (see Table 3.9), even though it is still very much in the theoretical stage . The payload mass was estimated to be on the order of 1×10^8 kg and a "worst-case" ΔV of around 150 km/s was used (see Chapter 2). If any methods can be found to lower either of these values to more reasonable levels, then perhaps a more technically mature propulsion system can be justified for the Emerald City.

The 150 km/s ΔV includes the ΔV required for both the "outward" leg from the nominal orbit to the target planet and the "return" leg from the planet to the nominal orbit. It was felt that it would be too difficult and costly in terms of mass and power to include a propellant synthesizing plant that would take compounds such as methane (C_2H_4) or water (H_2O) and break them down into molecular hydrogen and other gases on board the Emerald City. Depending on an on-board synthesizing plant would limit the destinations of the station to planets where hydrogen compounds were sure to be located either on the planet itself or on any of its moons. It would also require tremendous flexibility from the system designed to gather the compounds from their different sources and from the system designed to break down the different compounds into H_2. However, the aspect of propellant production was not examined in-depth during this first part of the project and it could be that the above points can be addressed in a satisfactory manner. If this is the case, then the ΔV's could be cut approximately in half since the Emerald City would be able to replenish its propellant supply at the target planet instead of only at the nominal orbit. A study would then have to be conducted to determine whether the reduction of the ΔV would be worth, from an "impulse required" point-of-view (see Equation 3.11), the increase in mass and power required that would accompany a propellant synthesizing plant. If it is found that it is worth putting the plant on board, then nuclear propulsion could be given further consideration as more of a near-term solution to the propulsion problem of Project WISH.

If antimatter propulsion is still found to be the best choice for the Emerald City, then more information will have to be found on this unique system. A more detailed study of such problems such as on-board antimatter storage and handling, conversion of annihilation energy into thrust, and shielding required can be examined, with emphasis on what effects these will have on the power system and mass of the station. Hopefully, some representative numbers can be determined on how much power would be required to generate the magnetic fields needed for the antimatter manipulation.

Finally, another aspect that has not been sufficiently dealt with during the initial stage of Project WISH is the effect that Equation 3.4 through 3.9 will have on the propulsion system. An antimatter system was selected mainly from the results of Equation 3.11 for impulse required. Next year, more emphasis can be put on Equations 3.4 through 3.9 and their meaning to the propulsion system, whether it be antimatter or nuclear. These equations were presented and graphed with the hopes that they can be put to use further down the road in determining optimum operating conditions for the chosen propulsion system of the Emerald City.

CHAPTER 4

VEHICLE DYNAMICS AND CONTROL

4.0 INTRODUCTION

This chapter describes the methods used to study necessary attitude dynamics and control based upon artificial gravity spin rate, orbital radius, body shape, and power required for stability. Methods of structural dynamics are also employed to determine the nature of the propulsion system-structural dynamics coupling, and establish basic design considerations.

Attitude dynamics and control studies are necessary for the Emerald City because there are many instances such as docking, orbit changes, debris evasion, etc. where attitude orientation is important. Since artificial gravity will be required for the Emerald City (see Chapter 5), a rotating ship is the only realistic design at this time to ensure the well-being of its inhabitants. However, a rotating ship dynamically constitutes a gyroscopic system. It is of major concern to orient the Emerald City in a stable configuration while in its nominal orbit. Thus, the stable equilibrium attitude orientations need to be determined.

Since equilibrium is really a special case, the system must be able to damp out disturbances. Therefore, the control needed for attitude stabilization must be found. Only the rigid body attitude dynamics is studied since coupling with flexible body dynamics is beyond the intended scope of this project, at this point.

Structural dynamics is taken up to assess the dynamic structural loading under expected high thrust and docking loads as well as discovering the extent as related to propulsion so that basic design parameters can be established. Using structural dynamics analysis, the crew station's acceleration is evaluated to design for allowable comfort levels through longitudinal axial dynamics and analysis of the rotating torus (See Chapter 9 for the preliminary configuration of the Emerald City).

4.1 ATTITUDE DYNAMICS AND CONTROL

Attitude dynamics of the Emerald City is first considered as an uncontrolled rigid body. By identifying the attitude configuration at which the space station is stable, it is expected that minimum power will need to be used to maintain attitude control. Should deviations occur from nominal attitude after determining the equilibrium configurations for a generic spinning body in a heliocentric orbit, a control system study will be done in order to assess the control power needed to return the body to its equilibrium. Through the equations of motion, it will be shown that the stability of the space oasis is dependent on body shape, rate of spin, and orbital radius. These parameters translate into astronautical terms as the structural configuration as reflected by the mass moments of inertia, artificial gravity as reflected by the nominal spin rate n_s, and parking orbit as reflected by the heliocentric orbital angular velocity Ω.

4.1.1 Equilibrium Attitude

Equilibrium analysis of the space station body begins with the equations of motion of a spinning body. From the angular momentum (h), equation:

$$\dot{h} = \frac{dh}{dt} = \Sigma T \tag{4.1}$$

where T denotes the applied torques. For a spinning body, the angular momentum vector is

$$h = I\omega \tag{4.2}$$

where I is the mass moment of inertia matrix and ω is the body's angular velocity vector. Application of Equation 4.1 leads to Euler's equations of motion:

$$[I][\dot{\omega}] + \tilde{\omega}[I][\omega] = [T]. \tag{4.3}$$

If ϕ is the rotation about the orbit normal, or precession, and θ the motion of the body out of the orbit plane, or nutation, then it was found that the states of equilibrium of the spinning body are:

$$\begin{aligned} \phi_{E1} &= \textit{arbitrary} & \theta_{E1} &= 0 \\ \phi_{E2} &= 0 & \theta_{E2} &= \arccos(rb) \\ \phi_{E3} &= \frac{\pi}{2} & \theta_{E3} &= \arccos\left(\frac{b}{(4r-3)}\right) \end{aligned} \tag{4.4}$$

where

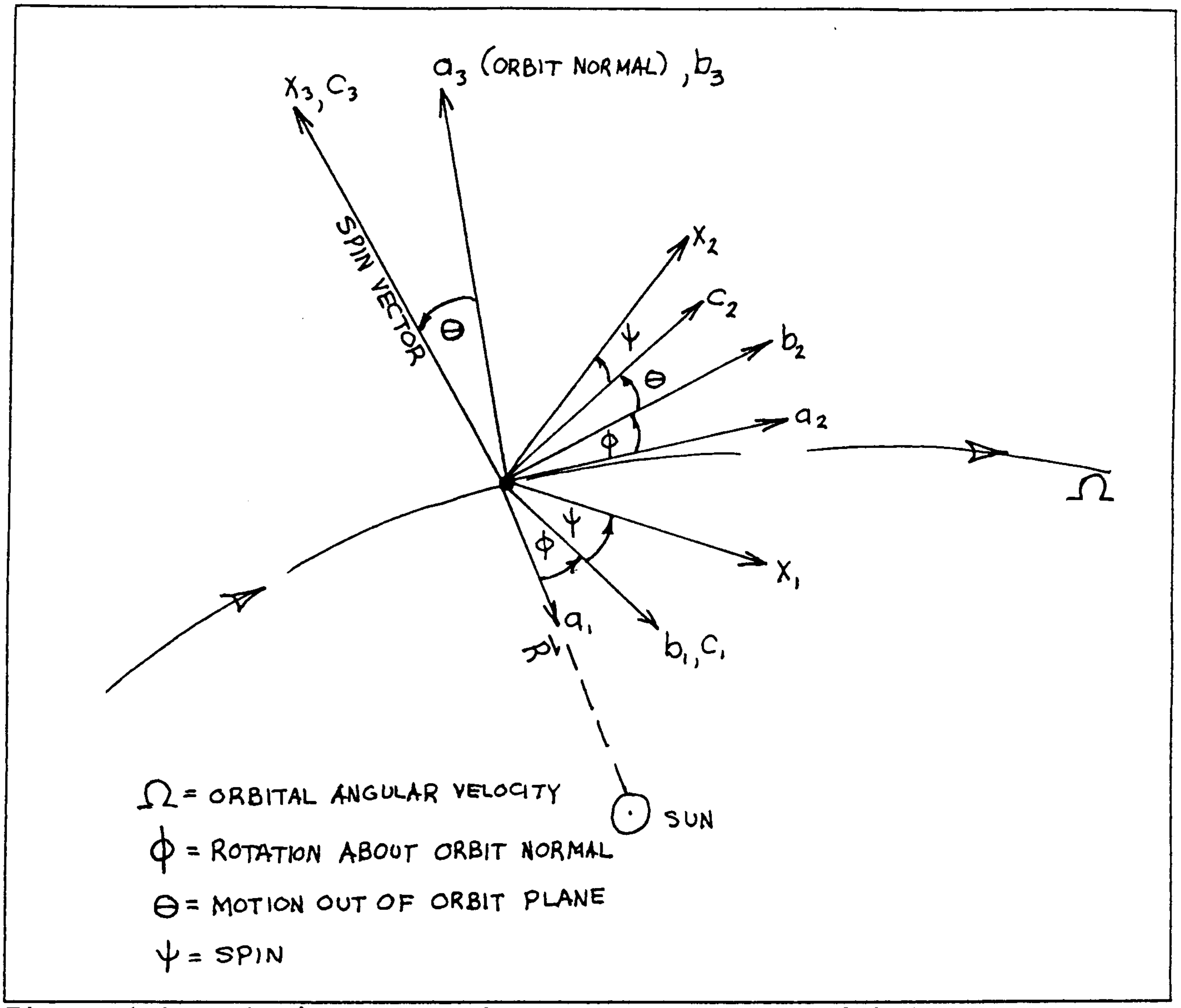

Figure 4.1: Euler's Angles of rotation to the Equilibrium Axes.

$$r - \frac{I_3}{I_1} - \frac{C}{A} - \textit{slenderness ratio}$$

$$b - \frac{n_s}{\Omega} - \frac{\textit{rate of body spin}}{\textit{orbital angular rate}} \qquad (4.5)$$

where I_3=C, I_1=I_2=A are the principal moments of inertia about the principal body axes x_1, x_2, x_3 (see Figure 4.1). It is assumed that

$$I_1 = I_2 \tag{4.6}$$

and that

$$\begin{aligned} \phi &= constant \\ \theta &= constant \end{aligned} \tag{4.7}$$

for equilibrium. Therefore, any time derivatives of precession and nutation will be zero. It is further assumed that the orbital angular rate is circular and constant. The orbital angular rate is a function of the orbital radius R, where

$$\Omega = \mathit{orbital\ angular\ rate} = \sqrt{\frac{GM}{R^3}} \tag{4.8}$$

where G is the universal gravitational constant and M is the mass of the sun.

4.1.2 Attitude Stability Analysis

The spinning body is then analyzed for small perturbations from the above equilibrium conditions (Eqs. 4.4). The equilibrium equations are linearized for small perturbations[24], and the resulting linear perturbation Equations (4.9) are used to establish conditions for non-diverging solutions of the perturbed angles ϕ and θ:

$$
\begin{aligned}
&\frac{1}{r}\ddot{\theta}+\Omega\left[b\sin\theta_E-\frac{1}{r}\sin2\theta_E\right]\dot{\phi}\\
&+\Omega^2\left[3\left(1-\frac{1}{r}\right)\cos2\theta_E\sin^2\phi_E+b\cos\theta_E-\frac{1}{r}\cos2\theta_E\right]\theta\\
&+\Omega^2\left[\frac{3}{2}\left(1-\frac{1}{r}\right)\sin2\theta_E\sin2\phi_E\right]\phi=0\\
&\frac{1}{r}\ddot{\phi}\sin^2\theta_E+\Omega\left[\frac{1}{r}\sin2\theta_E-b\sin\theta_E\right]\dot{\theta}\\
&+\Omega^2\left[\frac{3}{4}\left(1-\frac{1}{r}\right)\sin2\phi_E\sin2\theta_E\right]\theta\\
&+\Omega^2\left[\frac{3}{2}\left(1-\frac{1}{r}\right)\cos2\phi_E\sin^2\theta_E\right]\phi=0
\end{aligned}
\tag{4.9}
$$

which will yield the non-diverging critical stability conditions for the first, second, and third equilibrium configurations listed in eqs. (4.4), respectively:

$$
\begin{aligned}
&1.\quad b>\frac{1}{r}\quad \textit{and}\quad b>\frac{4}{r}-3\\
&2.\quad b<\frac{1}{r}\quad \textit{and}\quad r>1\\
&3.\quad b<\frac{4}{r}-3\quad \textit{and}\quad r<1
\end{aligned}
\tag{4.10}
$$

The stability conditions (4.10) are plotted in Figures 4.2 - 4.4.

Consider the stability plots for the configuration under study (see chapter 9), there will be extremely large values of b. That is, the artificial gravity spin rate will be much greater than the orbital angular rate. The shaded areas in Figures 4.2 through 4.4 are the ranges

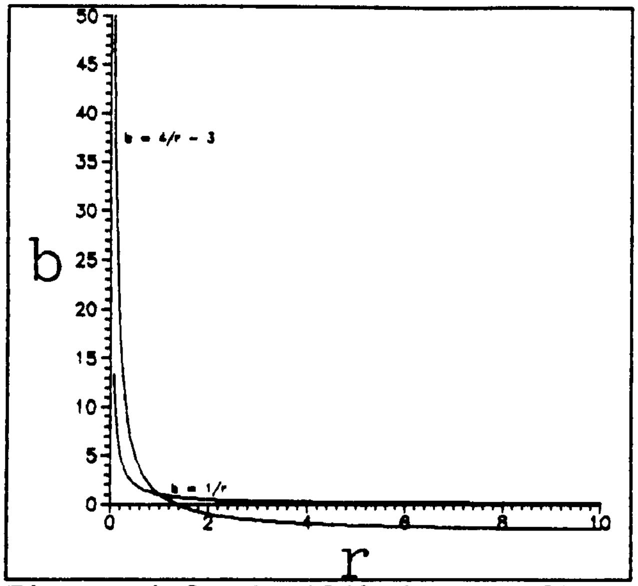

Figure 4.2: Equilibrium Configuration Case One, (4.10)

for which the station will be stable at the various equilibrium conditions.

Case One yields both slender (r<1), and stubby (r>1) configurations for high b or low r, meaning either the station must have almost no rotation (and no artificial gravity) or resemble a narrow rod to be unstable for equilibrium position one. Case Two, while allowing for numerous stubby configurations, does not have b values of any practical use for artificial gravity requirements. Case Three, at high b, requires the Emerald City to be an almost straight line, with no practical torus, to be in the stable region. Thus, cases two and three are of no practical use in the parametric studies at this time.

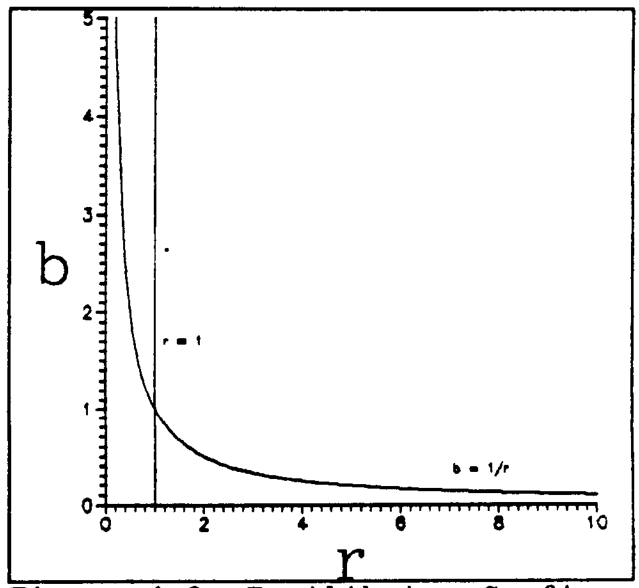

Figure 4.3: Equilibrium Configuration Case Two, (4.10)

These conditions will be used for configuration studies to help establish body size and shape as well as rate of spin for artificial gravity. The Orbital Mechanics group can also use these conditions to help determine possible low parking orbits when near planets. Plots of stability conditions help decide body rate of spin and orbital radius in relation to the body's shape. The stability plots relate r to b where r accounts for the body shape through the moments of inertia, and b accounts for the body spin rate and orbital radius through the equation

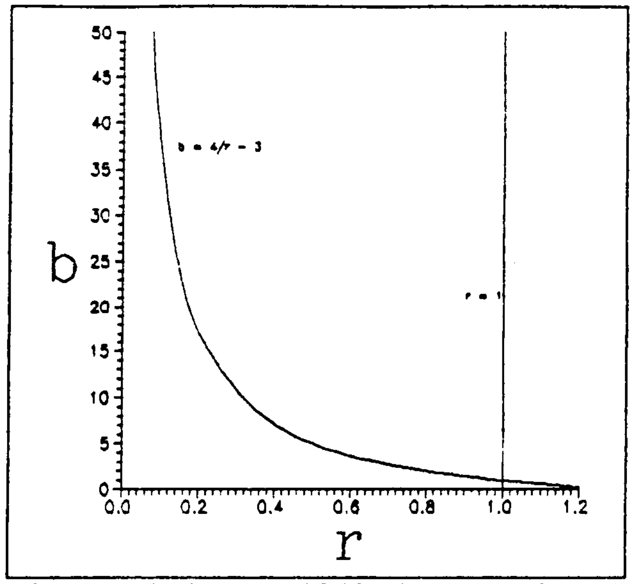

Figure 4.4: Equilibrium Configuration Case Three, (4.10)

$$b = \frac{h_3}{I_3\Omega} = \frac{I_3 n_s}{I_3\Omega} = \frac{n_s}{\Omega} \tag{4.11}$$

where n_s is the total spin rate about the axial (x_3) direction of the Emerald City, and h_3 is the equilibrium angular momentum about x_3.

The orbital radius is related to the nondimensional parameter b by

$$b = \frac{n_s}{\Omega} = \frac{2\pi n_{RPM} R^{\frac{3}{2}}}{60(GM)^{\frac{1}{2}}} \tag{4.12}$$

where n_{RPM} is the axial RPM of the station.

4.1.3 Attitude Control

The control system study is the next step in the vehicle dynamics and control. The parameters used to describe the system must first be changed from the Euler's angles, (ϕ,θ,ψ), to another set due to the singularities involved with Euler's angles. To avoid these singularities, angular rotations θ_1, θ_2, and θ_3 about equilibrium axes x_1, x_2, and x_3, respectively, are defined and used, the order of rotations being θ_2, θ_1, and θ_3. The control system study is done by deriving the linearized equations of motion for the body in a disturbed position from any one of the three equilibrium conditions described by Eqs. (4.3), in terms of perturbations in $\theta_{1,2,3}$ similar to Eqs. (4.9)[24]. For this analysis it can be assumed that the rate of spin of the body (due to artificial gravity requirements) is much greater than the orbital angular velocity and the gravitational terms can thus be dropped. After obtaining the linearized gyroscopic equations of motion in the general form:

$$[M]\ddot{q} + [G]\dot{q} + [K]q = [T], \tag{4.13}$$

where M,G, and K are the inertia, gyroscopic and stiffness matrices, the state variable method formulation is used to control and simulate the station dynamics. This is done for controlling perturbations from the equilibrium configuration E1 in Eqs. (4.4). The parameter values were chosen in accordance with the corresponding conditions in (4.10). Furthermore, at this point only the gyroscopic dynamics is of interest, hence θ_3 dynamics was not considered since it is non-gyroscopic. For equilibrium case one, after defining a nondimensional time ($\tau = n_s t$), the following equations were obtained[24]:

$$
\begin{aligned}
\ddot{\theta}_1 + n_s(r-2)\dot{\theta}_2 + n_s^2(r-1)\theta_1 &= T_1 \\
\ddot{\theta}_2 + n_s(2-r)\dot{\theta}_1 + n_s^2(r-1)\theta_2 &= T_2
\end{aligned}
\tag{4.14}
$$

yielding

$$
[\dot{x}] = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ (1-r) & 0 & 0 & (2-r) \\ 0 & (1-r) & (r-2) & 0 \end{bmatrix}[x] + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}[T]
\tag{4.15}
$$

At this point, MATRIX_X[25], a control analysis/design software package was used to design linear quadratic regulator controls for the performance measure

$$
PM = \frac{1}{2}\int(x^T x + T^T T)dt.
\tag{4.16}
$$

Applying unit initial conditions and using the state variable matrices, MATRIX_X produced the open loop and full state feedback control (closed loop) responses for r=1.5 (see Figs. 4.5 and 4.6) and r = 0.5 (see Figs. 4.7 and 4.8).

From the closed loop responses, the control power integrals[26] were computed by using MATRIX_X

$$
S = \frac{1}{2}\int T^T I^{-1} T\, dt
\tag{4.17}
$$

where T = the control torques and I = mass moment of inertia matrix which yields:

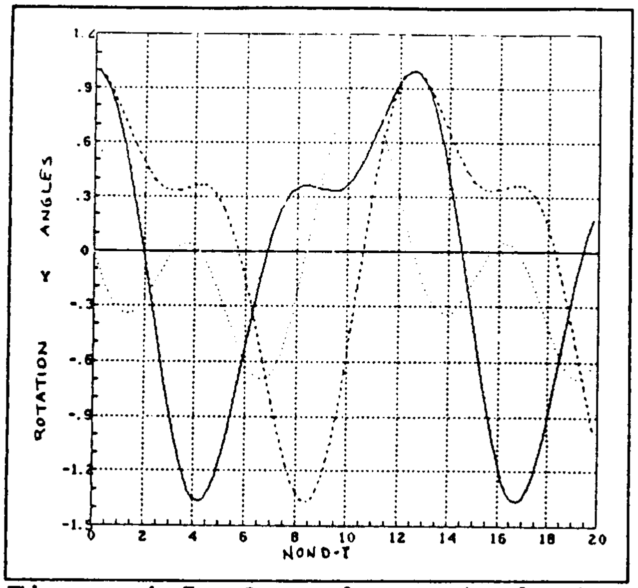

Figure 4.5: Open loop simulation for r=1.5

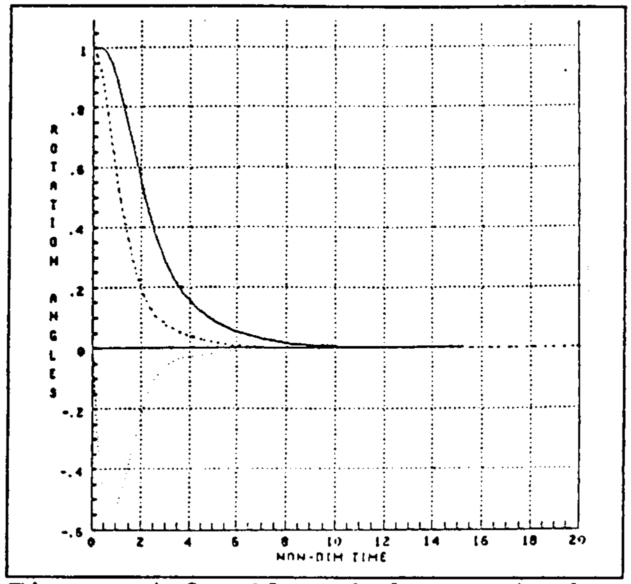

Figure 4.8: Closed loop simulation for r=0.5

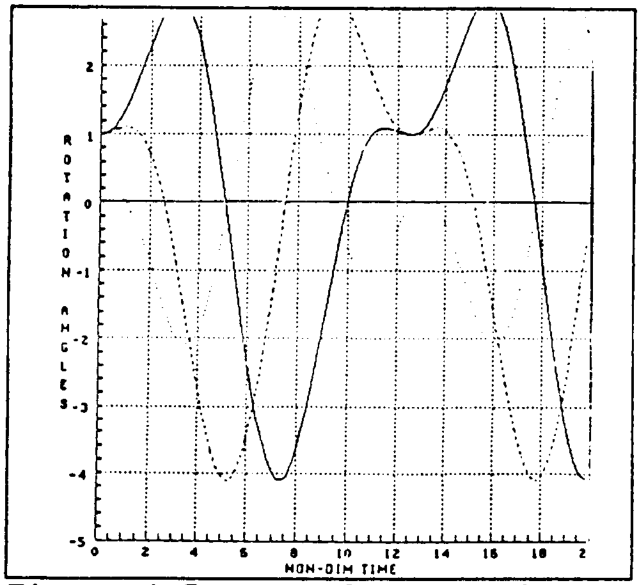

Figure 4.7: Open loop simulation for r=0.5

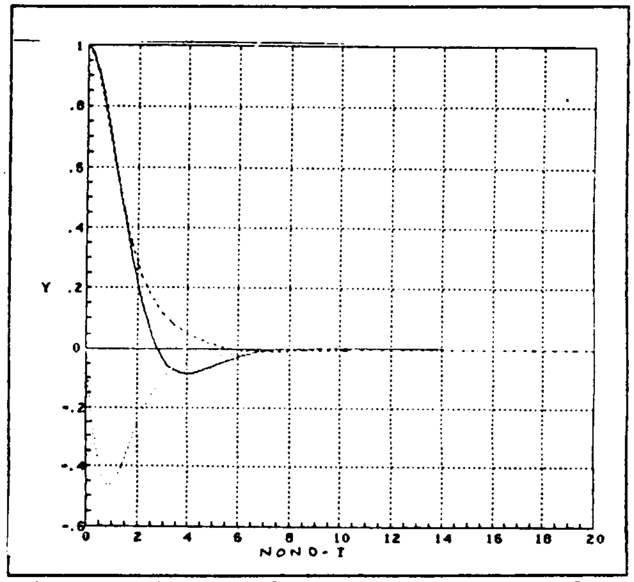

Figure 4.6: Closed loop simulation for r=1.5

$$S = \frac{1}{2} A n_s^3 3.78 \quad for \quad r = 1.5$$

$$and \tag{4.18}$$

$$S = \frac{1}{2} A n_s^3 12.36 \quad for \quad r = 0.5$$

From this, it is shown that a wider torus with a shorter stem (stubby configuration) will require less power for stability than a more slender body with a larger stem.

Now consider a simple example of control for the slender case with four control thrusters, two along each principal axis on the torus. It can be shown that

$$P_{RMS} = \frac{A v_{ex} n_s^2}{2D_t} \sqrt{\frac{P^*}{\tau_c}} \tag{4.19}$$

where P_{RMS} is the root mean square power for the trusters, A is $m_0 r_z^2$ (where m_0 is the total mass and r_z is the axial radius of gyration), D_t is the torus diameter, v_{ex} is the thruster exit velocity, n_s is the spin rate of the torus ($n_s = 2\pi/60\ n_{RPM}$), τ_c is the nondimensional time to damp out disturbances from MATRIX$_X$ closed loop simulation ($\tau_c = n_s T_c$, where T_c is the control period), and P^* is the value from the MATRIX$_X$ power integral analysis.

Table 4.1: Power requirement example.

m_0	= $25 * 10^8$ kg
r_z	= 1000 m
D_t	= 600 m
A	= $25 * 10^{14}$ kg m^2
v_{ex}	= 4000 km/s (chemical)
n_s	= 0.18
τ_c	= 10
P^*	= 12.36
P_{RMS}	= $3 * 10^{14}$ W

Table 4.1 evaluates the r=0.5 configuration using some sample values from Chapters 3 and 9.

Therefore it is found that the power required for the control thrusters is about 300,000 GW! This is a very rough inspection of the control power needed. It can be brought down by increasing the number of thrusters and/or their exit velocities. The above analysis has shown that the attitude control problem for the Emerald City is substantial enough to warrant further investigation.

4.2 STRUCTURAL DYNAMICS

4.2.1 Introduction

Simple, mundane systems can often be idealized as a rigid structure, whereby resulting in simple mathematical models. These models can then be applied with a minimum amount of effort to yield satisfactory answers to the desired questions. When the system exceeds some arbitrary complexity, the system can no longer be thought of as rigid. The space station under study in this paper, the Emerald City, is certainly far too complex a structure to be considered rigid. One form of analysis of such structures is a lumped mass modelling method which is considered adequate for the preliminary design phase.

This method spatially discretizes the continuum structure which exists in reality. The resulting multi-degree-of-freedom system is generally described by a set of second order ordinary differential equations. This system can then be solved through a modal coordinate transformation[27]. By transforming this system into the modal coordinate system, or the natural coordinate system, efficient solutions can be obtained. Modal analysis can also further aid in the understanding of the system under study.

The analysis of the Emerald City is broken up here into two steps. The analysis of a longitudinal system is first studied as a simplified model to provide some parameter evaluation that may be useful in configuration choices and in establishing the interaction of structural dynamics with the propulsion system parameters considered in chapter 3. Next a three dimensional system is defined to study the torus structure. This may also yield some important design considerations.

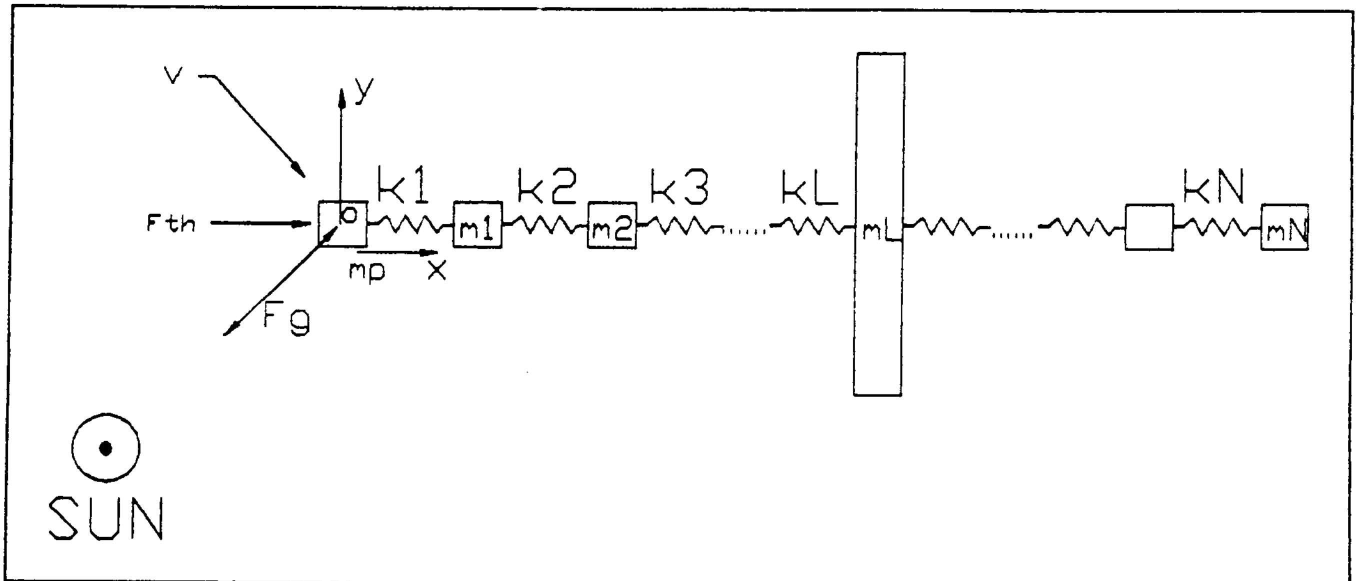

Figure 4.9: Longitudinal Structural Dynamic Model

m_p = Propellant Mass
m_i = Structural Mass (i = 1,...,N)
m_L = Crew Quarter Section Mass
k_i = Structural Stiffness
F_{TH} = Thrust
F_g = Gravity
v = Velocity

4.2.2 Longitudinal (Axial Dynamics)

The lumped-mass system modeled in Figure 4.9 is used to study the effect on the structural dynamics due to the axial thrust applied by the propulsion system and the docking loads due to shuttles. The desire here is to model this structure in such a way as to yield a system for modal analysis. The configuration shown in figure 4.9 is a lumped mass idealization of the preliminary configuration established for the Emerald City as presented in Chapter 9.

The space oasis is lumped into three different types of masses. The first is m_p. It is the propulsion system, including fuel, providing a time-variant parameter. The remaining structural masses are considered to be constant. All are equal except m_L, which is the mass of the torus section, or crew section, and is assumed to be some multiple of the other structural masses. The desire is to faithfully provide an acceptable longitudinal vibrational model for the change in mass due to the expulsion of propellant or axial docking of shuttles as support vehicles (see Chapter 9).

From the inertial reference frame, the acceleration of each mass, i, is:

$$a_i = \ddot{U}_o + \ddot{q}_i \qquad (4.20)$$

where $\ddot{U}_0$ is the acceleration of the vehicle center of mass. Therefore, the equations of motion for this mass are:

$$m_i(\ddot{U}_o + \ddot{q}_i) = -k_i(q_i - q_{i-1}) + k_{i+1}(q_{i+1} - q_i) \qquad (4.21)$$

By compiling all equations, assuming that the orbital motion and the structural flexibility are uncoupled, and with some rearranging the following is the result[24]:

$$[M_s]\ddot{q} + [K_s]\ddot{q} = -\vec{m}_s \ddot{U}_o \tag{4.22}$$

where

$$\vec{m}_s = [m_1 m_2 \ldots m_L \ldots m_N]^T$$

$$[M_s] = \begin{bmatrix} m_1 & & & & \\ & m_2 & & 0 & \\ & & \ddots & & \\ & & & m_L & \\ & 0 & & \ddots & \\ & & & & m_N \end{bmatrix}$$

$$[K_s] = \begin{bmatrix} k_1+k_2 & -k_2 & & & 0 \\ -k_2 & k_2+k_3 & -k_3 & & \\ & & \ddots & & \\ & & & \ddots & \\ & & & & \ddots \\ 0 & & & -k_N & k_N \end{bmatrix} \tag{4.23}$$

$[M_s]$ and $[K_s]$ are the mass and stiffness matrices which are defined in reference 4 and yield the following system:

$$[M]\ddot{q}(t) + [K]q(t) = Q(t) \tag{4.24}$$

It can also be shown that:

$$\ddot{U}_O = a_O = \frac{F}{m_o} \tag{4.25}$$

where $m_0 = m(t)$ is the total mass of the ship at time t, a_0 is the rigid body acceleration of the Emerald City at time t, and

$$F - F_{TH} + F_{GX} \tag{4.26}$$

F_{TH} is the thrust applied and F_{GX} is the gravitational force which is always present. For simplicity, gravitation will not be carried through since it will not affect the structural dynamic system considered appreciably. By dividing a representative common stiffness scalar, k, out of the stiffness matrix, then dividing the system by m, a similar common mass scalar, and applying the following nondimensional time transformation:

$$T - \Omega_{STR}\, t \tag{4.27}$$

$$\Omega_{STR} - \sqrt{\frac{k}{m}} \tag{4.28}$$

where Ω_{STR} denotes a characteristic structural natural frequency, distinct from the symbol, Ω, used in Section 4.1 denoting the orbital angular velocity. The following system results:

$$\Omega^2_{STR}[M'_s]\ddot{q}(T)+\Omega^2_{STR}[K'_s]q(T)=-\frac{\dot{m}_s}{m}\frac{F_{TH}}{m_o} \tag{4.29}$$

$$[M'_s] = diag[1\ \ 1\ \dots\ \epsilon\ \dots\ 1] \tag{4.30}$$

Note that $m_L = \epsilon m$. Also noticing that

$$F_{TH} = \dot{m}_p V_{ex} = \frac{m_{PTO}}{t_{PR}} I_{sp} g \tag{4.31}$$

the following forcing function results for the right hand side of Equation 4.29:

$$a_0 = \frac{F_{TH}}{m_0} = \frac{\zeta R_{PTO}}{1-R_{PTO}\eta} \tag{4.32}$$

where

$$m_0 = m_{0TO} - \dot{m}t = m_{0TO} - \frac{m_{PTO}}{t_{PR}}t$$
$$R_{PTO} = \frac{m_{PTO}}{m_{0TO}} \qquad \zeta = \frac{I_{sp}}{t_{PR}} \qquad \eta = \frac{t}{t_{PR}} \tag{4.33}$$

where R_{PTO}, m_{PTO}, and m_{0TO} are the take-off propellant ratio, take-off propellant mass, and total take-off mass of the station. The parameter ζ is the thrust to total propellant weight ratio consumed during the burn time, t_{PR}. Another way to look at the thrust force is through power parameters:

This is now in terms of the propulsive system power, W, as defined in Eq. (3.7). Rearranging for placement into the system of equations, the

$$F_{TH} = \dot{m}_p V_{ex} = \sqrt{\frac{2 m_{PTO} W}{t_{PR}}} \tag{4.34}$$

only change is:

$$\zeta = \frac{\sqrt{2\alpha t_{PR} \frac{R_{WO}}{R_{PTO}}}}{g t_{PR}} \qquad R_{WO} = \frac{m_W}{m_{OTO}} \tag{4.35}$$

where m_W is the dry mass of the propulsion system. The system represented in equation 4.29 can now be represented nondimensionally as

$$[M_s']\ddot{Q}(T) + [K_s']Q(T) = -m' \frac{\zeta R_{PTO}}{1 - R_{PTO}\eta'} \tag{4.36}$$

$$Q(T) = \frac{\Omega_{STR}^2}{g} q(T) \qquad \eta' = \frac{1}{\Omega_{STR} t_{PR}} q(T) \qquad m' = \frac{\vec{m}_s}{m} \tag{4.37}$$

Equations 4.32 through 4.37 relate explicitly the relationship among the longitudinal structural dynamics, the propulsion system parameters relevant to chapter 3, and the structural parameters to be chosen.

4.2.3 Modal Analysis

The above system in Equation 4.36 was then transformed into the modal system for analysis. By finding the modal matrix of the system that satisfies the following:

$$u^T [M_s'] u = I \qquad u^T [K_s] u = [\lambda^2] \tag{4.38}$$

$[\lambda^2]$ is the diagonal matrix containing the eigenvalues, or the squared natural frequencies, of the system corresponding to the eigenvector, or modal vector, in the modal matrix, u. *I* is just an identity matrix. The system now is transformed into

$$[I]\ddot{\eta}(T)+[\lambda^2]\eta(T)-[u]^T m'\left(\frac{\zeta R_{PTO}}{1-R_{PTO}\eta'}\right) \tag{4.39}$$

This system can then be efficiently analyzed and simulated.

The system discussed above, equation (4.39), was modelled with N=7. The torus, or crew section, m_L, was then allowed to be at any interior point with a variety of different size ratios ($m_L = \epsilon m$), from 1 to surely a maximum of 100 (ϵ = 1,...,100). Figure 4.10 illustrates the results for one position. This is for m_L at position 2 ($m_2 = m_L$ in figure 4.9), although all of the locations yield similar results. They show that for all sizes that currently seem possible, the natural frequency remains relatively unchanged. All seven modes corresponding to the seven degrees of freedom are presented. Notice that the maximum frequency is less than $2\Omega_{STR}$(it is for all positions also). It is of some importance when the simulation is desired.

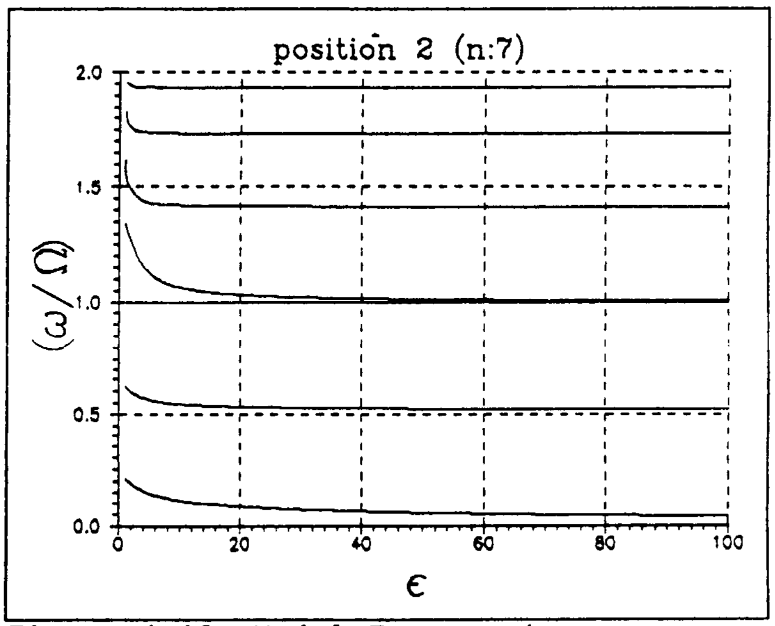

Figure 4.10: Modal Frequencies

For some insight into the accelerations obtained at the crew section, a look at Figure 4.11 is warranted. This diagram shows the crew section at the third position. The relative mass is 50 times that of the other mass sections. This graph plots all seven modes. As expected, the crew section shows almost no change except in the first mode, its critical mode. Its maximum acceleration is then proportional to this displacement multiplied by the first mode's frequency squared:

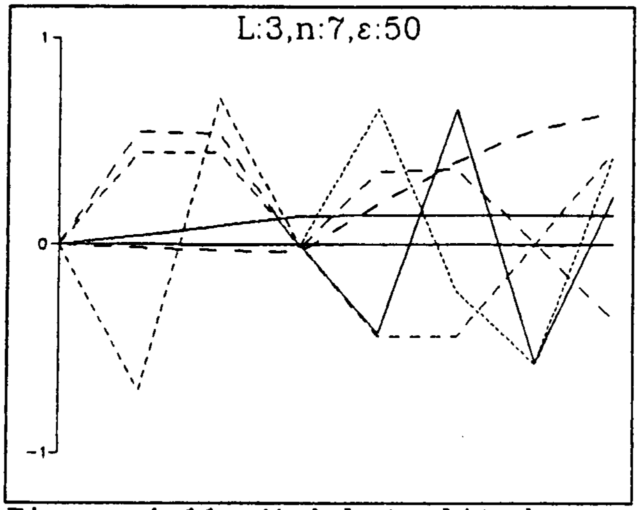

Figure 4.11: Modal Amplitudes at Structural Masses.

$$\ddot{\eta}_{Lmax} = \lambda_1^2 \eta_{Lmax} \qquad \lambda_1 = \frac{\omega_1}{\Omega_{STR}} \tag{4.40}$$

where η_{Lmax} is the maximum modal amplitude at m_L, where ω_1 is the first structural natural frequency.

This was produced for all positions, again at a variety of sizes. Figure 4.12 illustrates the results. Again for all sizes that currently seem plausible, it is a very smooth curve. Note that it predicts the maximum acceleration, for a mass ratio of 20, at position 6 to be approximately 0.4 the value at position 2. Note that position 2, being closest to the propulsion system,

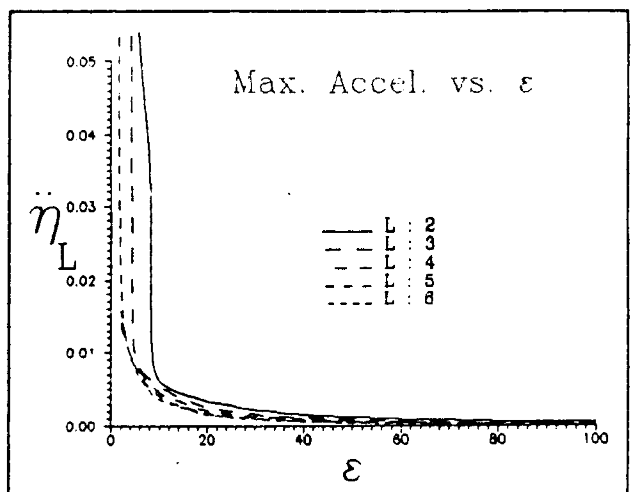

Figure 4.12: Modal Accelerations at the Crew Station as a Function of Crew Station Location

experiences the largest accelerations of the crew station, the effect diminishing as m_L is moved away from the thrust location.

Modal Analysis, as has been demonstrated herein, can provide many important parameter constraints desirable for the design of the Emerald City. From what has been shown here, the best location of the torus section, where the crew resides, can be determined with respect to the allowable acceleration levels which can be generated. Valuable information is also derived from plots such as Figure 4.11, which provide information about the maximum amplitudes along the axis. The structural design requirements for these sections are therefore available.

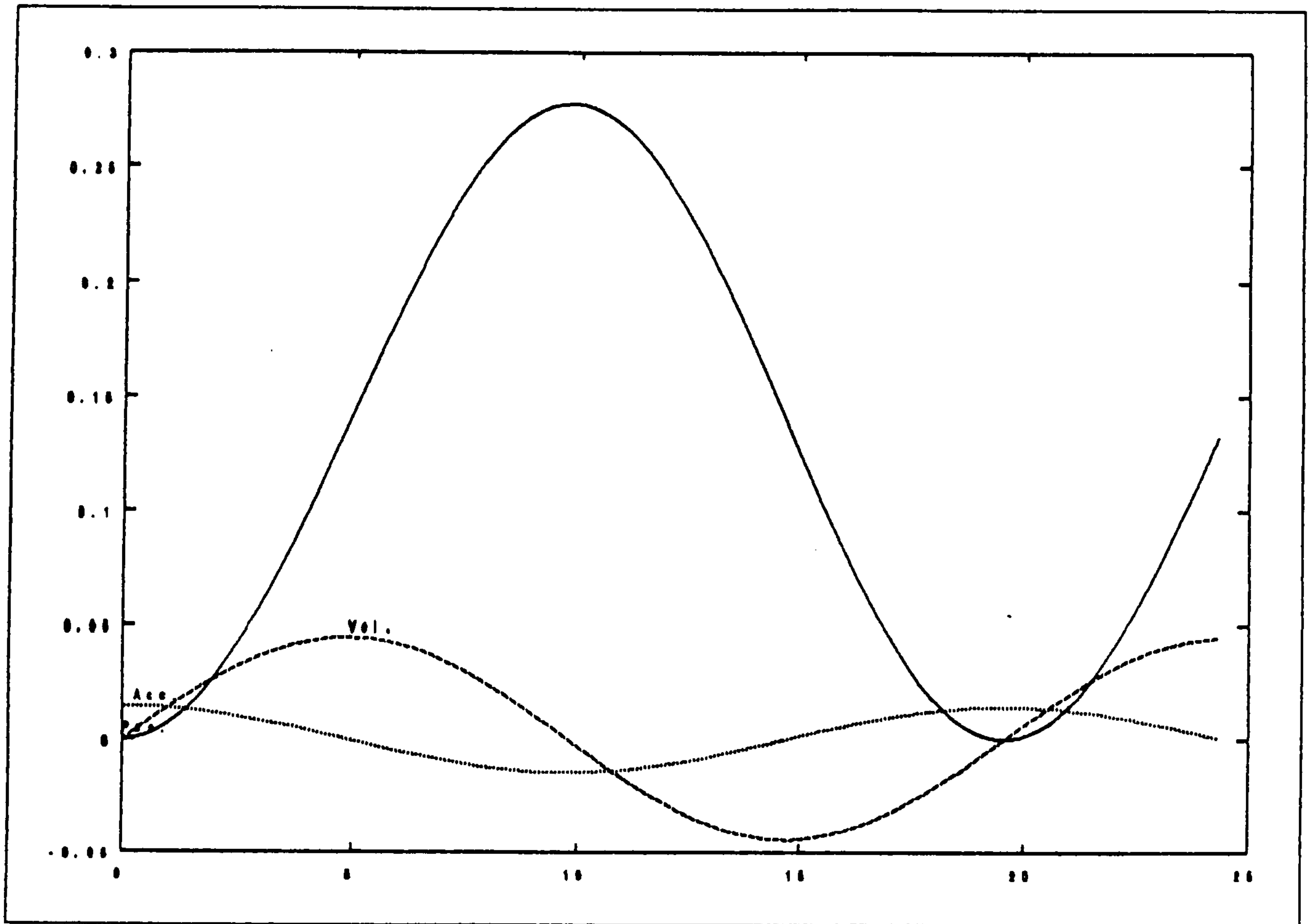

Figure 4.13: Response at Position 2
Modal Amplitudes vs. Nondimensional Time

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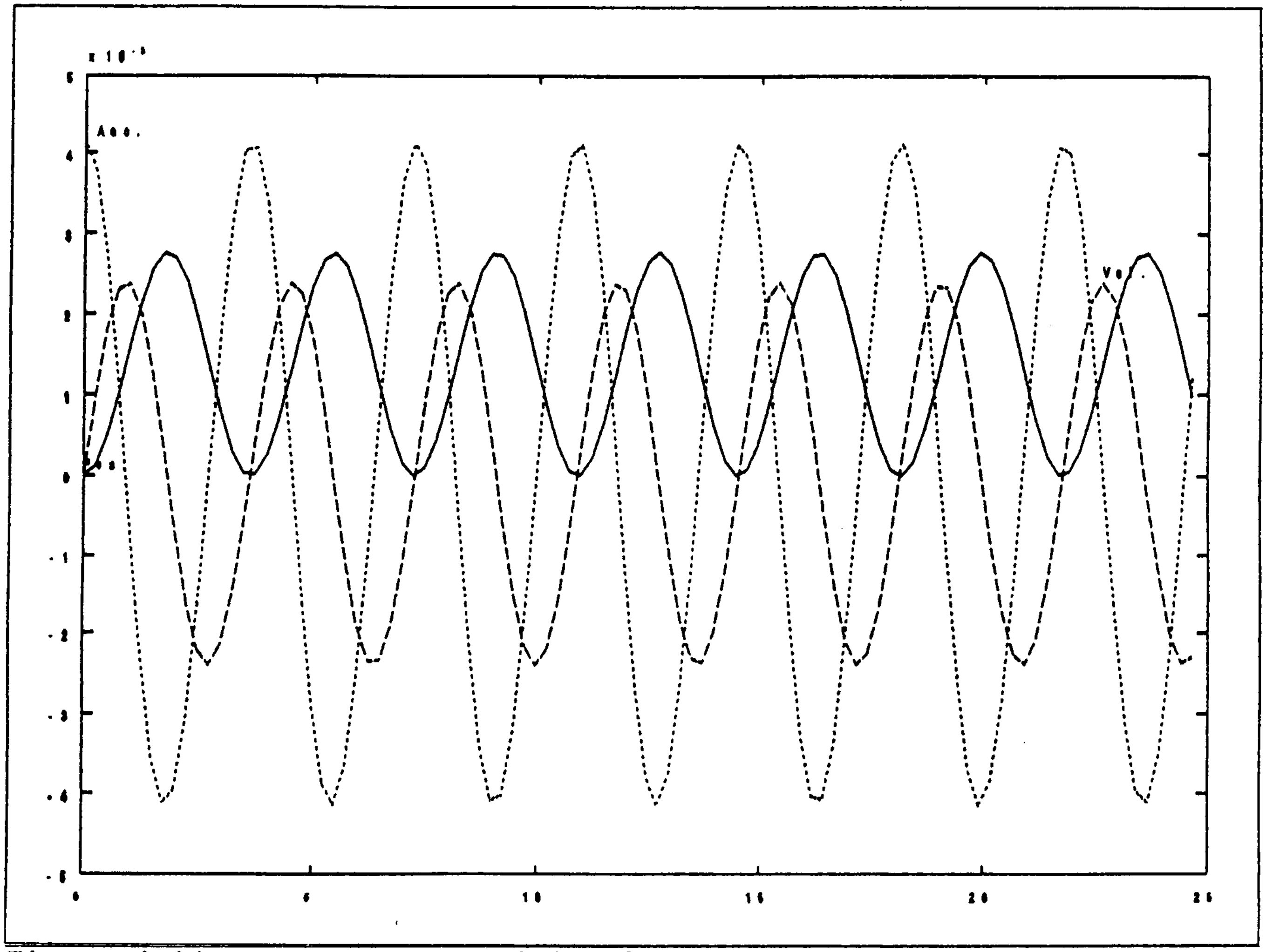

Figure 4.14: Response at Position 6
Modal Amplitudes vs. Nondimensional Time

Simulation

By introducing the modal state vector:

$$x(T) = [\dot{\eta}_1(T)\eta_1(T) \ldots \dot{\eta}_L(T)\eta_L(T) \ldots \dot{\eta}_N(T)\eta_N(T)]^T \tag{4.41}$$

the system can be simulated digitally in the form:

$$\dot{x} = Ax + Bu \tag{4.42}$$

where A is the system matrix and B is the input matrix for the input function, U, signifying thrust and docking loads. Figures 4.13 and 4.14 show the response due to the exact same forcing function input corresponding to a thrust input of Eq. 4.39 for the sample propulsion parameters (ζ = 0.05, R_{PTO} = 0.5), a relative crew size of 20 (ϵ = 20), with the initial state vector = <u>zero</u>, and torus locations at positions 2 and 6 (L = 2 and 6), respectively. Notice that the maximum acceleration for position 6 is approximately 0.4 the value at position 6!. A similar result was found through the modal analysis.

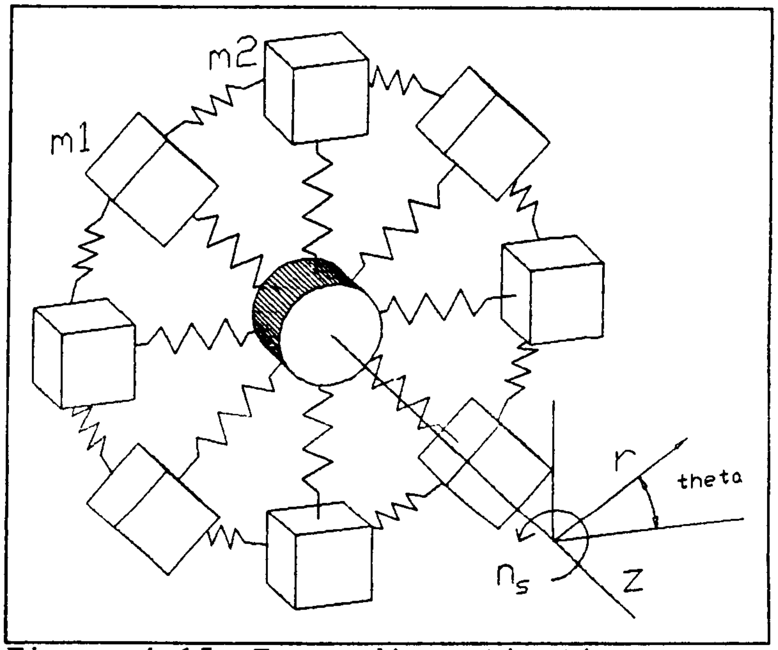

Figure 4.15: Torus discretization

<u>4.2.4 Torus Analysis</u>

Such a large structure requires detailed analysis at every level. Therefore, the next step seems to be a study of the structural dynamics of the torus section. The section is then idealized as a ring of interconnected masses all connected to the center hub, as shown in Figure 4.15. The system can then be studied for the optimum number and strength of the "spokes", as well as the necessary strength required by the torus section itself.

The module used for analysis is shown in Figure 4.16. The stiffness values include both axial and bending components for both in-

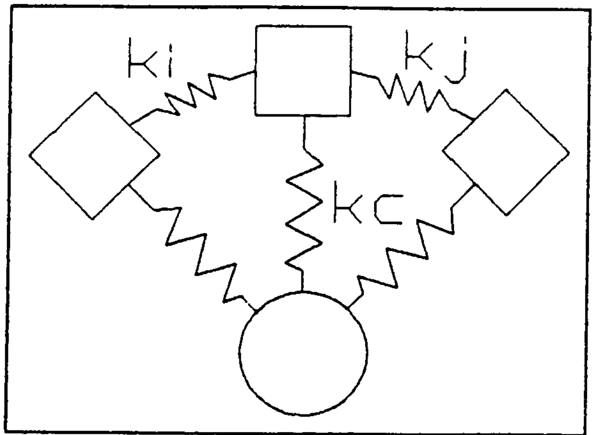

Figure 4.16: Torus Module

plane and out-of-plane since, in general, they will be different.

Similar to the longitudinal system, the kinetic and potential energies are[24]

$$T = \frac{1}{2}\dot{u}^{T}[M]\dot{u} + n_s\dot{u}^{T}[F] + n_s^{2}[F]^{2} \tag{4.43}$$

$$V = \frac{1}{2}u^{T}[K]u \tag{4.44}$$

This system takes into account the rotational dynamics of the station in n_s which is the rotation rate and is then governed by Lagrange's equations:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{u}}\right) - \frac{\partial L}{\partial u} = Q(t) \tag{4.45}$$

where

$$L = T-V = \frac{1}{2}\dot{u}^{T}[M]\dot{u} + n_s\dot{u}^{T}[F(u)] + n_s^{2}[F^{2}(u)] - \frac{1}{2}u^{T}[K]u \tag{4.46}$$

is the Lagrangian of the system. 'u' is the total flexible displacement vector of the torus elements m_i including radial, circumferential and longitudinal (out-of-plane) displacements. [M] and [K] represent assembled mass and stiffness matrices. F(u) is a vector function of flexible displacements u. Applying the Lagrange's Equations (4.45) yield:

$$[M]\ddot{u} + [G]\dot{u} + [K']u = Q(t) \tag{4.47}$$

which represents a gyroscopic system of equations due to the steady state rotation rate, n_s, of the torus to yield artificial gravity for the crew.

This system can then be analyzed and simulated to study the parameters involved and how they effect the design.

4.2.5 Conclusion

Any system this large and complex cannot be thought of as rigid. Therefore, some thought has to go into the effects of its flexibility. The longitudinal modal system discussed previously is currently being used to study the non-dimensional parameters derived herein in order to find design constraints which may exist. The torus section analysis is still in its infancy but is expected to follow the same path and further add to the structural as well as other subsystem's design.

CHAPTER 5

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS)

5.0 INTRODUCTION

This system is responsible for meeting all of the requirements necessary for human life aboard the space station. The life support systems for the Emerald City will operate within a completely closed environment subject to resupply every six years or more. This was chosen based on a three year flight time to the destination, any stop-over at the destination, and three years flight time back to the nominal orbit. This report defines all requirements which must be met in order to sustain a population of 500-1000 people. In addition to defining what conditions must be met, an effort to find mechanisms capable of meeting these requirements was made. Figures for power and mass of the complete ECLSS were obtained both per man and also assuming a crew size of 700. The ECLSS was divided into the following integrated subsystems:

Temperature and Humidity Control System (THCS)
Air Revitalization System (ARS)
Atmosphere Control System (ACS)
Water Waste Management System (WWMS)
Solid Waste Management System (SWMS)
Nutritional Supply System (NSS)
Radiation Shielding (RS)

The systems are designed to operate under a centrifugal acceleration equal to one Earth gravity.

5.1 ECLSS SPECIFICATIONS

Shown in Table 5.1 is an initial estimate of mass and power requirements of an ECLSS system for the Emerald City[(28),(29),(30)]. To obtain the mass storage value, a 99% recovery of all water processed was assumed. The figure represents the loss of water over a six year period, pulls an additional 25% added for storage tanks.

Table 5.1: ELCSS Mass and Power Estimates

ECLSS	MASS (Kg/man)	POWER (W/man)
ACS	284	70
ARS	452	200
WATER	21	---
CLOTHES	20	---
WWMS	35	250
WATER STORAGE	550	---
SWMS	15	80
NSS (PLANTS)	200	2000
NSS (STRUCTURE	1200	---
SUBTOTAL	2617	2850
x 700 MEN	1.83×10^6 kg	2.0MW

Each of the ECLSS subsystems discussed in the introduction will be discussed below.

5.1.1 Temperature and Humidity Control

This system is responsible for maintaining all equipment within the station at normal operating temperatures. Also, it will control air temperature, humidity and ventilation. Cabin air temperature will be maintained at 72^0 F, and relative humidity will be 55 %.

This is a description of the thermal control system given in the VGRF report. Internal cooling is provided by active water transport loops. The waste heat collected by these loops is directed to a central bus heat exchanger. The bus exchanger acts as the interface to the heat rejection system. The external thermal control system uses modular radiators 3 m x 14.8 m x 0.2 m. The design is an aluminum honeycomb structure with fluid pipes within. Contact heat exchangers (aluminum to aluminum contact) interface the radiators to the transport loops.

The station that this TCS was designed for has a heat rejection requirement estimated between 20 to 25 KW for a crew of six. Making a linear assumption, the heat rejection requirement for this space ship will be 3 to 5 KW per man. Humidity will be controlled by circulating air through a condensing heat exchanger. Water collected from here will be sent to the WWMS to be purified.

5.1.2 Air Revitalization

This system is responsible for maintaining proper levels of oxygen, carbon dioxide and nitrogen in the station's air.

The systems most commonly used in the past in carbon dioxide reduction has been Sabatier or Bosch processes[30]. These are possibilities, but the Sabatier system has an undesirable byproduct (methane), and Bosch requires very high operating temperatures. For this ECLSS, a newer technology was explored.

Table 5.2: Air Composition

GAS	PRESSURE (N/m^2)	PERCENT COMPOSITION
Oxygen	2194	22
Nitrogen	7878	78
Carbon Dioxide	400	0.3

The system chosen was a carbon dioxide reduction method developed by Nitta, Ogughi, and Kanada[29]. Inlet gas of this recycle system is a mixture of carbon dioxide, oxygen and nitrogen. A filter removes trace contaminants. Carbon dioxide separation will be accomplished by a chemical absorption and desorption method using various types of solid amine beds. A schematic of the separation is shown (see Figure 5.1).

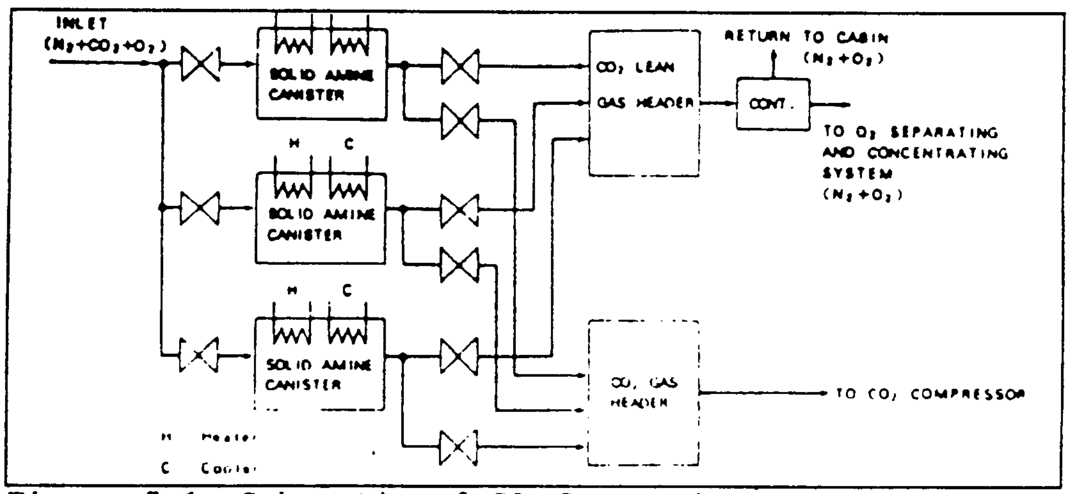

Figure 5.1: Schematic of CO_2 Separation

Oxygen separation is accomplished by absorption and desorption processes using salcomine and ethylene. From this process, nitrogen is separated and stored or released as is necessary.

The system to generate oxygen has been determined to be Water Vapor Electrolysis (WVE)[31]. WVE has advantages over other conventional ARS's in that cabin air is processed directly. WVE operates independently of any carbon dioxide separation system. Also, WVE acts as a partial humidity control system. WVE operates by drawing moist air into the anode compartment. Water vapor condenses onto the electrolyte and is dissociated into oxygen and hydrogen ions (H+), also electrons are released. Products from the anode compartment are oxygen enriched air reduced in humidity. On the cathode side, hydrogen ions join with free electrons to form gaseous hydrogen. The process requires electrical energy, and waste heat is produced (see Figure 5.2).

Some other advantages of WVE are relatively low operating cost and power. Operational life is expected to be ten years, after which time the units must be replaced. Because WVE units are small, they can be more efficiently used in areas with high or low crew concentrations than a centrally based system. Also, the WVE has few interfaces. This means the units are practically portable and therefore represent a more reliable or safer system than other ARS's. Each WVE unit is capable of meeting the oxygen consumption requirements of three crewmen. For a station of 700 men, 234 WVE units would be needed for use to meet the minimum oxygen consumption.

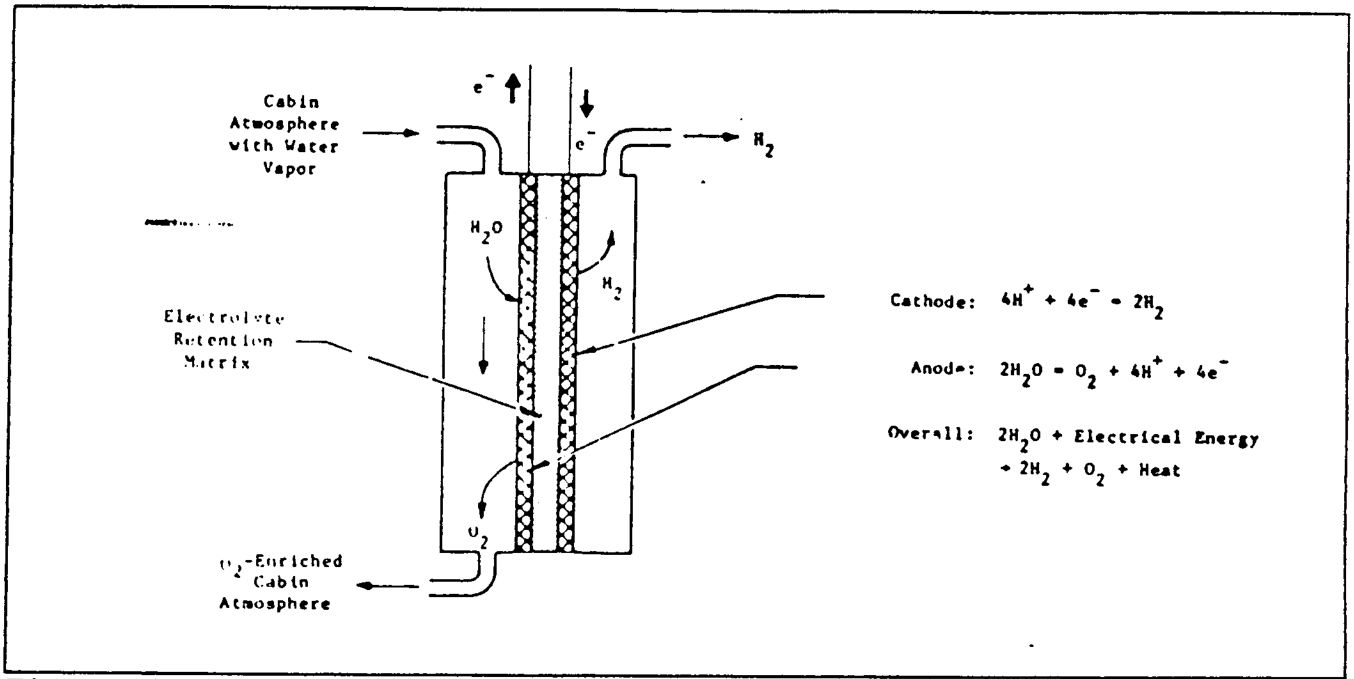

Figure 5.2: Water Vapor Electrolysis

Table 5.3: WVE Specifications

unattended operation	90 days
operating life	10 years
power	600 W/unit
weight	45Kg/unit
volume	0.11m
oxygen production	2.4 to 3.0 Kg/day *

* requirements of 3 men

5.1.3 Atmosphere Controls

This system is responsible for removing any harmful contaminants or dust particles from the cabin air. Contaminants will be removed by the three processes of: activated charcoal bed removal, chemisorption (lithium carbonate), and catalytic oxidation. Dust particles will be removed by filters used in conjunction with the air circulation system[30].

5.1.4 Water Waste Management

The estimated quantity of water to be recycled per man in a closed environment is roughly 20 kg per day. For this reason, the first requirement a WWMS must meet is high recovery of processed water. The leading candidate to be used aboard the proposed US space station Freedom is Vapor Compression Distillation (VCD). The most significant characteristic of VCD is that recovery of recycled water is 96 %. It should be noted that in a 700 member closed environment, VCD would lose almost five million kilograms of water every year. For this reason, VCD is not considered a practical solution for a long duration closed environment's WWMS.

The only WWMS found to operate at acceptable efficiencies (greater than 99 %), was a thermopervaporation method, shown schematically in Figure 5.3.

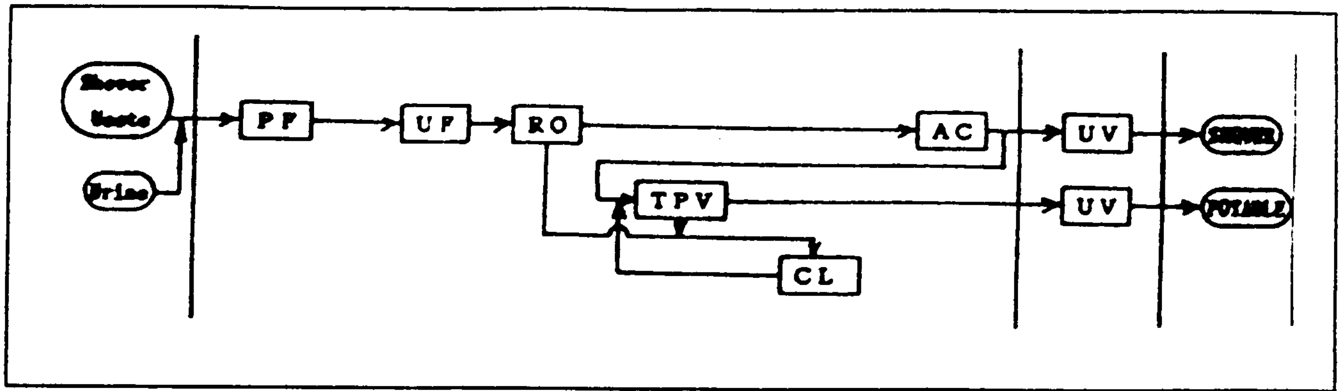

Figure 5.3: Schematic of Waste Water Management System

Explanation of the schematic:

- PF - Prefiltration rejects miscellaneous particles contained in shower waste, urine, and other sources.
- UF - Ultrafiltration rejects organic macromolecules and suspend ed solids.
- RO - Reverse osmosis removes solvent ions.
- AC - Activated charcoal removes trace organic materials.
- UV - Ultra-violet sterilization reservoir
- TPV - Thermopervaporation
- CL - Crystallizer removes any remaining solids.

5.1.5 Thermopervaporation[32]

Water vapor is passed over a hydrophobic membrane (polytetrafluoroethylene). The vapor passes through the pores of the membrane surface. Then, the vapor diffuses to reach the cooling surface where it condenses. A temperature differential between the feed vapor and the cooling surface provides the driving force through the membrane.

Because of the extensive filtration steps and processes to remove solvents, thermopervaporation is expected to have recovery rates greater than 99 %. This system enables the use of low quality heat (excess from other systems) to be used. Also, the water recovered is of very high quality, suitable for potable use. Using the thermopervaporation WWMS, there will be a water loss aboard the station of 51000 kilograms per year. This figure also represents the amount of water which must be held in storage to make up for this yearly loss.

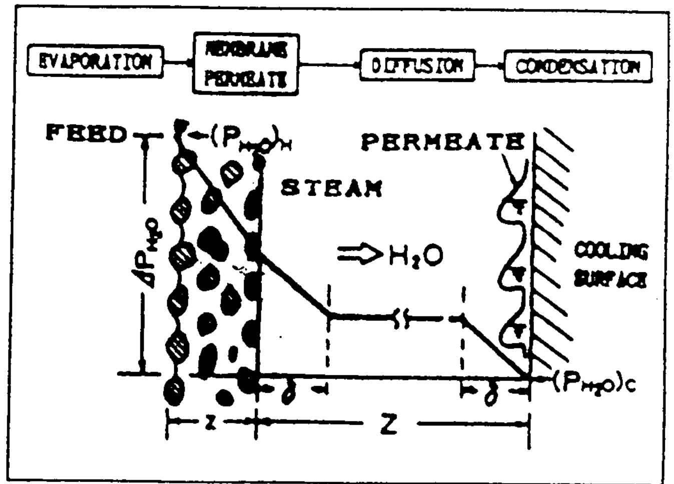

Figure 5.4: Thermovaporation

Table 5.4: Estimated Loads on Solid Waste Management System

	(Kg/man/day)
FECAL WASTE	.11
TRASH	.82
FOOD WASTE	.62
PLANT WASTE	2.76
TOTAL(man)	4.31
x 700	3017 kg/day

5.1.6 Solid Waste Management

This system must process all fecal, plant, food and trash waste. The objective is to recover minerals so that they may be used repeatedly in the hydroponics of the Nutritional Supply System. The most likely solution[33] to the SWMS is some type of wet oxidation.

5.1.7 Radiation Shielding of Inhabited Areas

The principal risk from space radiation is cancer. The following limits have been recommended[34] for lifetime radiation exposure without substantial increase in risk to obtaining cancer.

AGE (years)	FEMALE (rem)	MALE (rem)
25	100	150
35	175	250
45	250	320
55	300	400

Based upon these values, the acceptable dosage of radiation received aboard the space station would be no more than 10 rem per year. This assumes the space station will not be able to replace crewmen for maximum periods of ten years.

Shielding of the living quarters of the station will be from Galactic Cosmic Radiation (GCR), and from Solar Particle Radiation (SPR). Radiation from these two sources consist mostly of protons and some helium ions. The possible shielding material to be considered for the Emerald City is aluminum. An aluminum shield 8 gm/cm will allow an exposure to GCR and SPR of 11 rem/year during trans-planetary flight between Earth and Mars at Solar minimum activity. It is recommended that certain areas of the station be shielded with much higher levels of aluminum (20 to 30 gm/cm), where crewmen can retreat to during solar flares or other periods of increased radiation exposure.

5.2 ARTIFICIAL GRAVITY

Human beings have a psychological and biophysical need for artificial gravity. Although this need is not fully understood, it is believed that the body begins osteoporosis, fluid loss and general muscle atrophy immediately upon arrival in zero gravity. No one knows for sure if these effects are permanently damaging, but if the occupants ever wished to return to Earth, or any form of gravity, they will have to be subjected to some acceleration comparable to Earth gravity for at least part of each day.

A centripetal acceleration can be induced on the occupants by spinning the ship. This action would "stick" them to the walls much like a carnival ride. There are two factors which must be taken into effect when designing a habitat using this form of artificial gravity, spin rate and coriolis effect. An average human being does not enjoy more than 3 rpm for extended periods. Also it is not desirable to have a large gravity gradient between the head and the feet, which is created at a high rpm by the difference in their distance from the spin axis.

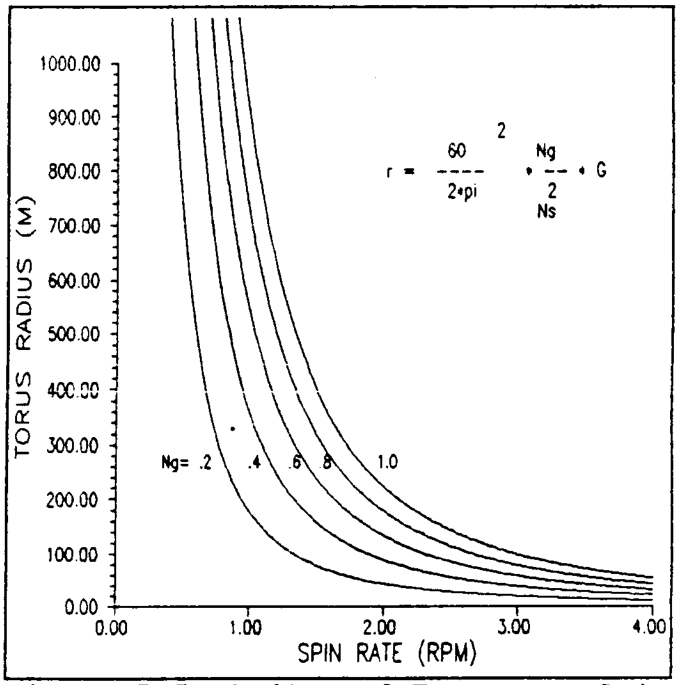

Figure 5.5: Radius of Torus vs. Spin Rate for Different Gravity Levels

The Emerald City has been designed with these considerations in mind. For example, an average radius of 270 meters and a spin rate of

1.6 rpm is required to maintain 0.8 g's. This rate is slow enough for human comfort, and it also induces a relatively small coriolis effect. The change in effective gravitation over a 3 meter radial change is 1%, and the change in gravitation across the entire living area is only 20%. With the spin increased to 1.81 rpm the crew can enjoy the same gravitation as we have here on earth. Figure 5.5 shows the relations between spin rate n_s, average radius, and induced acceleration N_g. A spin rate of 3 rpm has been determined as an upper bound for human comfort. Other boundaries will be dictated by attitude control, structural integrity, and other subsystems.

Of course, sections of the ship near the hub will have much smaller accelerations. Some sections may also be de-spun to provide microgravity for experimentation and recreation.

Based on these numbers, a radius of 270 meters and a spin rate of 1.6 rpm was suggested from the artificial gravity viewpoint. The values for radius and spin rate will also be affected by the results of the Vehicle Dynamics and Controls study found in Chapter 4 and the numbers suggested here are only preliminary.

5.3 MISCELLANEOUS LIFE SUPPORT CONSIDERATIONS

5.3.1 Social Structure

Some thought has been put into determining what sort of social structure the ship will require. This is an important issue if 500 to 1000 people are going to depend on each other and be productive for extended periods.

For a military type ship, the social structure has already been determined. There are books of regulations and etiquette written for naval ships and submarines. However, it was felt that the ship should not be completely populated by military personnel, but should be able to support any variety of crew make-up.

The Emerald City, like any other city, will need some sort of governing body involving a mayor and a police force. The fact is however that nearly everyone would be involved in public works maintaining and operating the ship. The crew and the state should be under separate authorities to prevent the state from using the environmental control as a means controlling actions.

The society may tend to have a class stratification between the ships crew and the passengers, who may be scientists, settlers or even asteroid miners. This sort of thing should be avoided by hosting social events. An antagonism present between these two groups could prove fatal in a time of emergency.

Another imposing issue is the adoption of an economic system. On this size ship there is no competition in food production and the very survival of the citizens is offered by the crew. There is no room for anyone who could not pay their bills.

This comes to the conclusion that perhaps upon entering the community a contract should be signed where the crew agrees to provide environmental control, food and housing and the passenger will provide certain services. Of course extensive checks would be made before leaving Earth, because if a contract is breached in outer space there is no turning back.

Under these economic conditions there is still room for money for buying non essential items, such as clothes, alcohol and nonessential foods. Also the citizens would share in any profits earned from exports or costs of any import. The money system would have to be compatible with earths so that upon return the citizens could lead an earth based life again.

Another important obligation of the government will be schooling and medicine. It is unreasonable to believe that men an women will be living and working together for twelve years and children will not be born. These children require schooling and everyone requires medical attention occasionally.

Perhaps the only model of such a community on earth is in the prehistoric tribes and nomads. These people faced the same problems of providing food, shelter, clothing and schooling as our modern travelers. Although now we have thousands of years experience in social interactions and technology.

There are a lot of questions raised at this point and many of the answers depend on the position of social concepts when the ship is launched. The agreements of the maiden crew and passengers will be the only means to determine the answers.

5.3.2 Medical Facilities

The Emerald City will have medical facilities to provide all of the necessary medical needs of the crew and any persons brought aboard as part of a rescue mission. These facilities need to have the capacity to do physical exams, attend to medical emergencies, and even do major surgery. Quarantine capabilities will also be required. The nature of the Emerald City and its mission will make the demand on the medical facilities fluctuate greatly. During routine operations, the demand should be small and limited to routine checkups and first aid. In the case of a rescue or major accident, the demand will be high and specialized skills may be required. To meet the fluctuating demand, the medical staff will consist of a small main staff on constant duty and an auxiliary staff, who will also be part of the research personnel on-board. This will provide the necessary flexibility and medical expertise.

CHAPTER 6

SUPPORT SYSTEMS

6.0 INTRODUCTION

Aside from the major systems on board the Emerald City, essential support systems must also be included in the design configuration. These support systems encompass communication systems for important data transmission and reception, radiation shielding for the crew and vital equipment, a shuttle craft or crafts for resupply, and a maintenance and industry capability. These support systems will be the focus of the sections in this chapter.

6.1 COMMUNICATIONS

As the Emerald City travels throughout the solar system, it must possess the ability to effectively communicate with Earth, various space colonies, and other spacecraft. To effectively communicate, vast amounts of information must be continuously transmitted and received for the entire length of the mission. There are two possible communication systems available for space application:

1. Microwave Systems
2. Optical Systems

Microwave systems are used extensively in Earth-orbit communication satellites because of their compatibility to the rest of the communication community, and also their performance in atmospheric conditions. For use as a communication alternative for the Emerald City; however, a microwave system suffers from two very important problems.

The first problem is its relatively small available bandwidth. Although this bandwidth is large enough for Earth-bound communication, the amount of data transfer capability for the Emerald City will require a far more flexible bandwidth to work with.

The second more crucial problem is the fact that microwaves systems, due to their inherent lack of extremely high beam directivity, would require an enormous amount of power to maintain a usable signal at very long ranges.

An optical system, on the other hand, is ideally suited for use on board the Space Oasis. It possesses a bandwidth over 20,000 times larger than the microwave spectrum, and it also can be easily used for long range communication because of its very high directivity. These optical communication systems are similar in component structure to other forms of communication systems, with only a few minor differences.

6.1.1 Laser Communication System

A laser communication system consists of the following major components:

1. Modulator
2. Laser Transmitter
3. Transmitter Antenna
4. Receiver Antenna (with Photodetection device)
5. Demodulator

The modulator takes an electrical signal and turns it into a transmittable form. The laser transmitter provides the modulated signal with enough energy to reach its destination in a usable state, while the transmitter antenna reduces the beam's divergence as much as possible. When the carrier beam reaches the receiver antenna, the antenna focuses the beam on a photodetector, which senses the intensity of the energy, converting it back into a usable signal to be demodulated. Each of these components are discussed in the sections that follow.

Modulation and Demodulation

Modulation is the varying of the amplitude, frequency, or phase of a carrier wave by either Analog or Digital techniques. Demodulation is just the inverse of this process.

An analog system continuously varies the amplitude, frequency, or phase of the carrier wave, whereas a Digital system uses a sampled data process which codes the signal by assigning a discrete symbol, usually a "one" or a "zero", to each data sample.

"For space communication systems, amplitude modulation is very rarely used because of undesirable noise characteristics"[35]. More common practice involves a phase or frequency shift to represent a binary one or zero, which is the basis for digital modulation. It follows from this fact that modulation and demodulation by digital methods will be the most practical form for the Emerald City's communication system.

Laser Transmitters

A laser (Light Amplification by Stimulated Emission of Radiation) works in the following simplified manner:

1. Excitation energy is applied to a laser material.
2. Atoms in a "ground state" jump an energy level "3".

3. Atoms then decay spontaneously to energy level "2".
4. From energy level "2", atoms decay to the "ground state" by spontaneous emission and radiate energy at a given frequency.

If the energy difference between level "2" and the "ground state" is large enough, the radiated energy will be at an optical frequency.

Lasers can be classified as one of three different types:

1. Solid State
2. Semiconductor
3. Gas

Solid State lasers are not very applicable to communication systems due to their low repetition rate and low efficiencies[36]. Semiconductor lasers have an advantage of being relatively low in mass, high in power, and high in efficiency; however, a semiconductor laser produces a fan shaped beam, and it requires cooling equipment because of its inherent heat problems.

A gas laser offers the best communication characteristics. These characteristics include a very flexible wavelength capacity throughout the optical spectrum, continuous operation without heat problems, and a highly stable and coherent beam.

Antennae Design

Transmitters

A laser transmitter usually uses an optical antenna to reduce the beam's divergence. Since beam divergence is inversely proportional to antenna aperture diameter, the transmitter antenna should be design as close to the diffraction limit as possible. This results in the smallest transmitter antenna size.

Beamwidth, denoted by θ, is limited to about a minimum of one microradian[37], and is related to wavelength, λ, and antenna diameter, d_t, by the equation[38]

$$\theta - 1.22\frac{\lambda}{d_t}$$

A graph showing the diffraction limited antenna sizes for various wavelengths throughout the optical spectrum is given in Figure 6.1.

Receivers

A receiving antenna can be either a reflecting type device (usually parabolic), or a refracting type lens similar to a transmitter antenna. The purpose of the antenna is to focus the incoming carrier beam on the photodetector. The sizing of the receiver antenna is governed by many

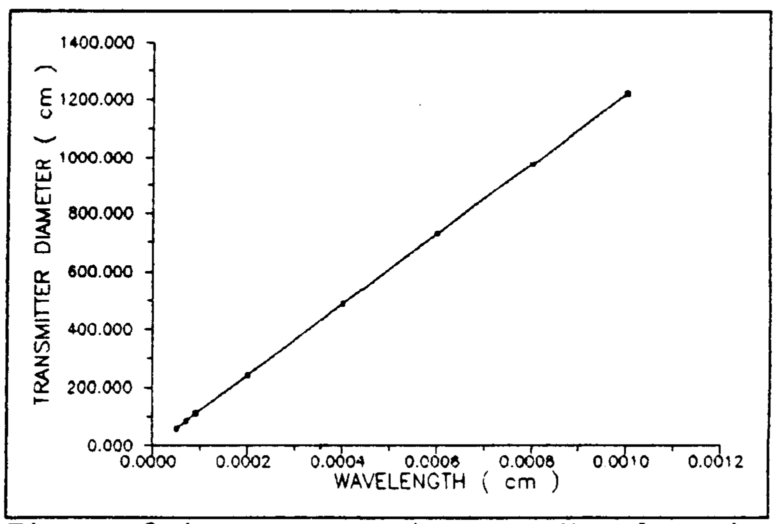

Figure 6.1: Antenna Size vs. Wavelength

factors, including noise considerations, communication range, data rate, carrier wavelength, and transmitter power.

Noise Considerations

With any communication system, both internal and external noise plays a considerable role in the degradation of the carrier signal being received properly by the photodetector. Some major noise sources found in the design of communication systems are:

Internal	External
Thermal noise	Photon fluctuation noise
Flicker noise	Radiation intensity noise
Current noise	Phase noise
Dark current shot noise	

The determination of the signal to noise ratio (SNR) for any particular communication system is a rather involved process; however, at least a factor of ten is required for adequate communication.

6.1.2 Communication Range

It has been decided, that due to propulsion constraints, the Emerald City will not travel much past the orbit of Saturn. This consequence puts the maximum range of communication (with the Earth and Saturn on opposite sides of the Sun) at approximately 12 A.U., twelve times the distance from the Sun to the Earth.

A few considerations should be added to this requirement to allow for obvious and not so apparent circumstances. A first point is that

Earth and the Emerald City will not always possess a direct line of sight between each other due to intervening planets or the Sun. To solve this problem, relay stations in the form of space colonies or satellites can be used. These solutions would cut the range requirement down considerably. A second problem that might arise is a need to communicate at ranges greater than 12 A.U. The capability should therefore exist for ranges up to almost 30 A.U. to fully encompass any emergency situation.

6.1.3 Data Rate

A high quality television channel can be transmitted using a 25 Mbit/s data stream. A voice circuit of equal quality requires approximately 32 kbits/s[39]. Using these two parameters as guides, an estimation of the data rate requirement can be determined.

Given that the maximum number of people on board the Emerald City will be 1000, a data rate of 32 Mbits/s will be reserved for their use. The amount of other data is questionable because there will obviously be a very intelligent computer system running the myriad of systems on the Space Oasis. However, for approximation purposes, an equivalent of 500 high quality television channels should suffice, resulting in a data rate of 12,500 Mbits/s. The final total data rate for adequate communication is then 12,532 Mbits/s.

6.1.4 Available Wavelength

As was mentioned in the introduction, the optical communication spectrum is enormous when compared to the available microwave range. Wavelengths from the near infrared (.001 cm) to the visible violet (.00005 cm) are the limits of the optical spectrum. In choosing the optimal wavelength for the communication system, it should be noted that the smaller the wavelength, the smaller the antenna and power requirements will be for a given communication system. For an optimal system on the Emerald City, a wavelength near the visible violet range is the most desirable.

6.1.5 Transmitter Power

To determine the required transmitter power, P_t, the range equation for communications is necessary. For laser-based communication systems, this equation takes the form of[36]

$$P_t = \frac{2.215\lambda R^2 hcB(SNR)}{d_t^2 d_r^2}$$

P_t - transmitter power
λ - wavelength
R - range
h - Planck's constant
c - speed of light
B - data rate (bits/s)
SNR - signal to noise ratio
d_t - transmitter diameter
d_r - receiver diameter

where R is the range, h is Plank's constant, B is the data rate in bits/s, c is the speed of light, SNR is the signal-to-noise ratio, and d_t and d_r are the transmitter and receiver diameters, respectively. From this range equation, valuable information regarding the scope of the required communication system for the Emerald City can be determined.

Setting the range at 12 A.U., data rate at 12532 Mbits/s, carrier wavelength at .00005 cm., the transmitter antenna diameter at 61 cm., and the signal to noise ratio at 10, variations in the required diameter of the receiver antenna can be observed in Figure 6.2 by varying the transmitter power. From this graph, a 500 kW laser system results in a 71.6 cm. receiver antenna diameter. This is more than adequate for the communication system; however, a tenfold increase in the SNR more than triples the diameter of the antenna (see Figure 6.3).

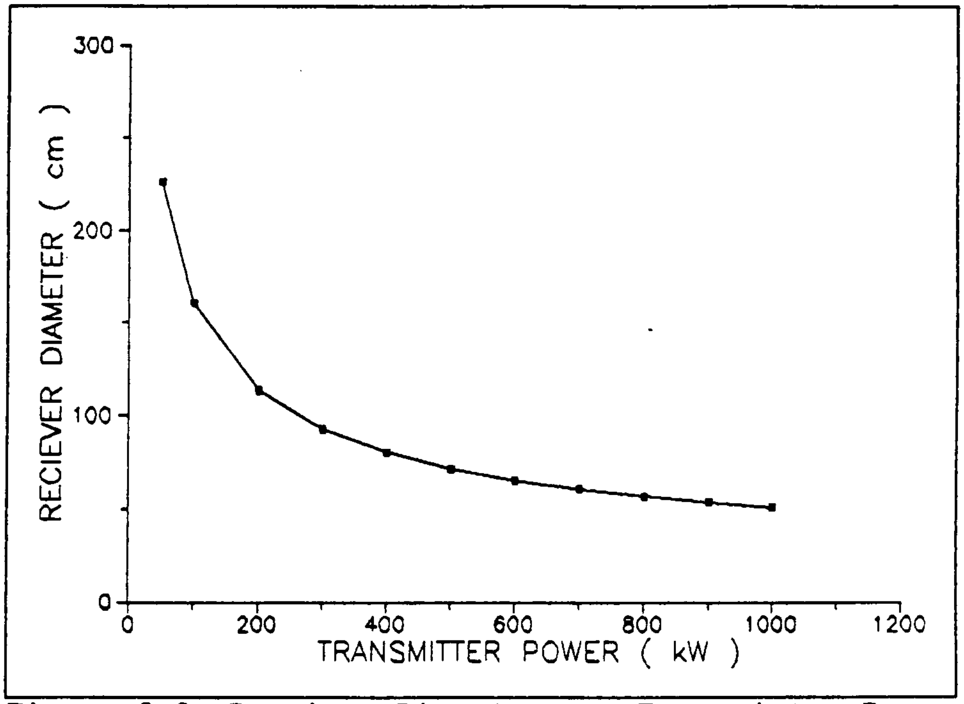

Figure 6.2: Receiver Diameter vs. Transmitter Power

Varying the wavelength for a 500 kW laser communication system to determine the effect on receiver diameter is shown in Figure 6.4.

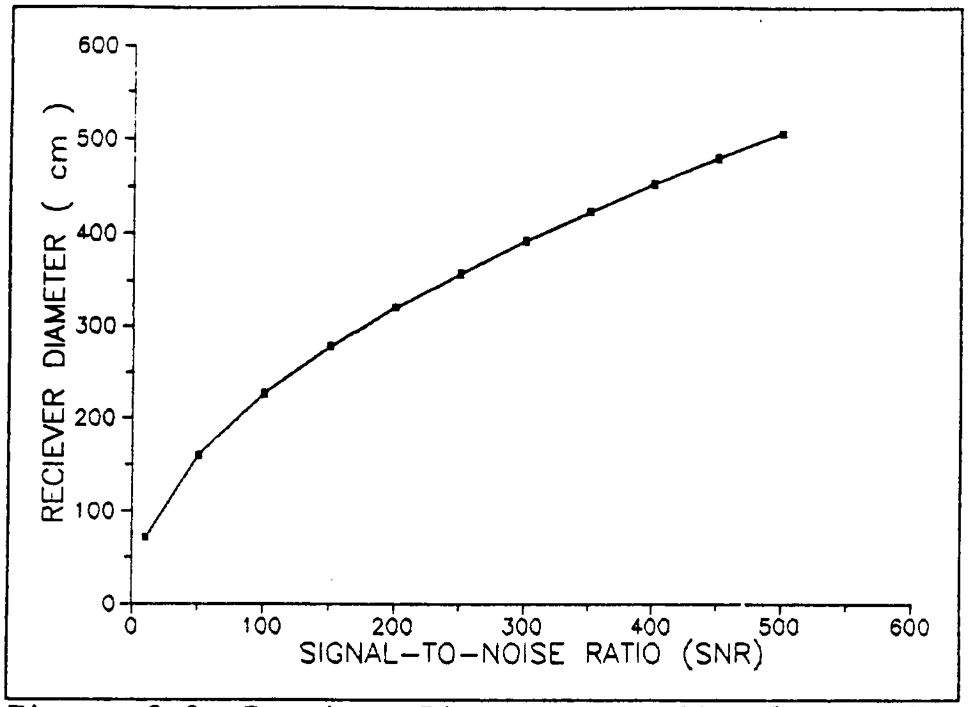

Figure 6.3: Receiver Diameter vs. Signal-to-Noise Ratio

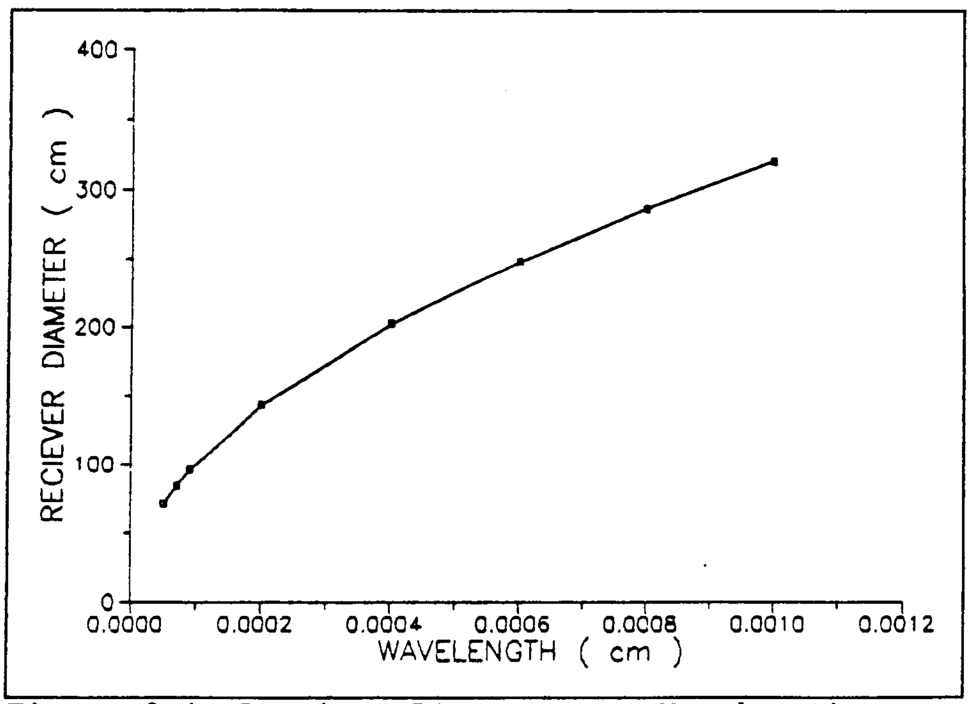

Figure 6.4: Receiver Diameter vs. Wavelength

Finally, using the same constant values as in Figure 6.2 except for setting the receiver diameter equal to 71.6 cm. and varying the communication range, the emergency capability of the communication system can be observed with respect to transmitter power requirements[37].

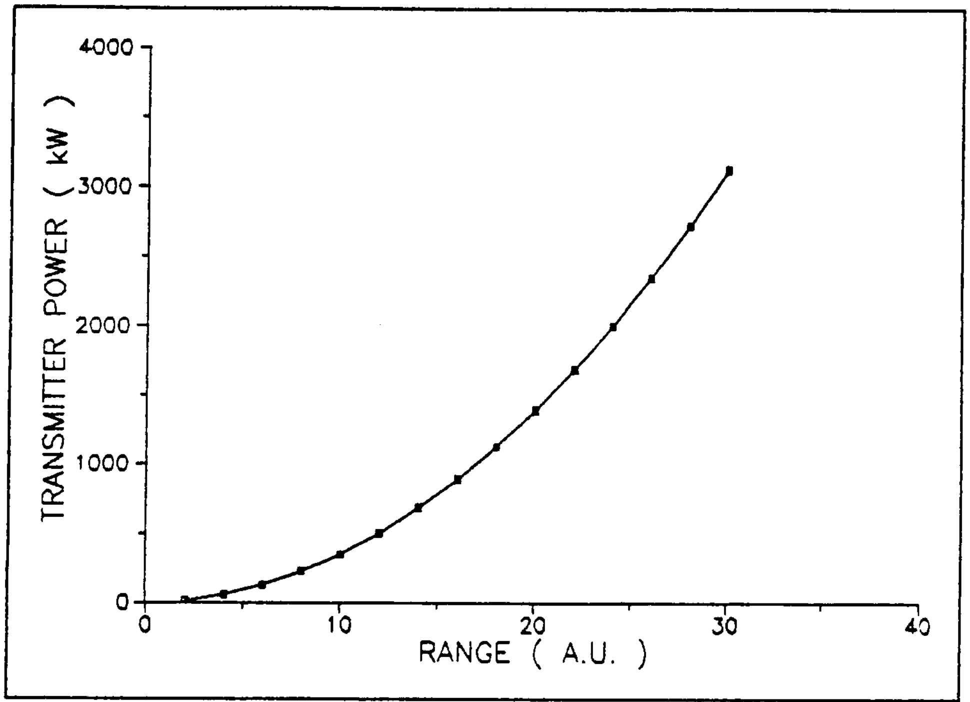

Figure 6.5: Transmitter Power vs. Range

6.1.6 Power Budget

From the previous figures, a 500 kW laser system seems to be the optimal design for the Emerald City. It possesses a modest power requirement, and also encompasses relatively conservative antenna sizes. Should this system be unable to satisfy the received signal constraints of a distant photodetector, the capability to increase the power should be available.

Also to be considered in the power budget is a multiple system design. It is not likely that the Emerald City will exclusively communicate with just Earth; therefore, more than one laser transmitter and receiver combination should be included in the final configuration. A system using four such units (four transmitters, four receivers) would be desirable. This would allow for at least three different communication links being connected at once, with a fourth unit down for regular maintenance.

From these considerations, a power budget of 5 MW should be allocated for the communication system. Although only 2 MW would be required for a fully optimal system, this figure could easily double in reality and still allow for an extremely long range "emergency link" to be used if needed.

6.1.7 System Mass Estimation

The mass of the total system can be broken down into its major components. The antenna masses for both the transmitting and receiving antenna will be similar due to their similar sizes. An approximation of 50 kg. per antenna should allow for size ranges of up to three or four feet in diameter.

As for the rest of the communication system, the transmission and receiving equipment will take up most of the total mass, resulting in approximately 1100 kg. per set[37]. Summing the entire four unit communication system gives a value of almost 5000 kg. Compared to the Space Oasis, this is a very small amount of mass, and even a doubling or tripling of this figure will not be of consequence to the stability of the space station.

6.1.8 Conclusion

The optimal communication system for the Emerald City will consist of four communication units containing both transmitter and receiver equipment. These units will be capable of linking effectively with networks over 12 A.U. away and also retain the capability to link with units over 30 A.U. distant. The flexibility of the system is of primary concern because the communication needs of the Emerald City might very well change over a course of fifty years. For this reason, the laser communication system is designed with allowances for increases in data rate and power requirements.

6.2 SHUTTLE (RESUPPLY)

It is not reasonable to design a ship of this size that can dock with another ship of comparable size. The control problems and forces for a rigid connection are great. A flexible bridge is feasible, but a more versatile solution is the use of shuttles.

A shuttle system would take care of routine missions, such as resupply of fuel, transfer of personnel to another ship, planetary exploration or as an emergency life raft (although the question of who will come to the rescue has yet to be addressed!). In this way the main ship will never be in orbit around a planet, and will never have to dock with a large, dangerous fuel storage ship.

The number of shuttles would have to be determined on the basis of their size, payload carrying capacity, and the requirements of the Emerald City.

6.3 MAINTENACE AND INDUSTRY

The residents of this unique community will be very similar in many respects to those in an prehistoric tribe. They will have little outside trade and will have to be completely self-sufficient. The modern tribe will be required to produce more than food and clothes, they will also have to produce and control their atmosphere as well as replace pieces of machinery that fail.

The ship will require food processing stations, textile production, machine shops and engineers to take care of power and propulsion. Much of the actual labor can be automated. This is especially true for nuclear reactor refueling and maintenance. A fleet of versatile robots or remotely operated machines would be needed for most extra-vehicular activities.

A single major time consuming and dangerous activity would be the search and repair of leaks in the hull. A robot operating on tracks, like a window washer, could accomplish this task effectively with little danger to the crew.

Another consideration is that all utilities will need to be regulated. This will require a massive network of powerful computers with many backups and safeguards. This system could not afford to fail.

Overall, the ship will be a very high tech integrated machine so that if one piece fails, another can take its place, much like the human body.

Chapter 7

POWER SYSTEM

7.0 INTRODUCTION

The Emerald City space station will be a self-supporting city of 500-1000 inhabitants, composed of numerous subsystems. Each of these subsystems requires electric or thermal energy to operate successfully. A power source that is capable of delivering continuous power to each of these subsystems needs to be identified and developed.

7.1 GENERAL CONSIDERATIONS

There are several considerations that must be observed when choosing a system that will fulfill the mission requirements. The system must provide continuous power at all times, and not be limited by the location of the space station. The system must also be capable of delivering increased amounts of energy when propulsion is being used, as the propulsion system will require an enormous amount of power.

Specific power and total mass of the power system are two important quantities that must be addressed. Specific power is simply the amount of power delivered per kilogram of the reactor. Total mass includes all of the supporting systems required to keep the power source functional. If solar power is used, the total mass includes the support structure, replacement cells, and any heat removal system. If a nuclear reactor is used, total mass includes shielding, structure, radiators, spare parts, etc.

A final consideration is reliability. The Emerald City cannot survive for any length of time without power. Maintenance must be quick and easy, parts and fuel must be available, and a backup system must be ready for use at all times.

With this in mind, a power system will tentatively be chosen for the Emerald City that will meet all criteria.

7.2 POWER BUDGET

In order to determine the large amount of electric power that will be needed to satisfy the functions of these systems, a power budget must be obtained. The subsystems of the station requiring electric power are grouped into the following categories:

1. Propulsion
2. Life support
3. Communications
4. Dynamics and Control
5. Thermal Subsystems
6. Shuttle and Maintenance
7. Misc. power (ie. computers, recreation, factor of safety, etc.)

A preliminary power budget is shown in Table 7.1. These estimates may change as each system is further analyzed.

The propulsion system requires a large amount on electric power. However, due to the speculative nature of the antimatter drive discussed in Chapter 3, no estimate has been made.

Table 7.1: Power Budget - Estimated

System	Electric power
Propulsion	several GWe
Life support	3 MWe
Communications	5 Mwe
Dynamics and Control	several GWe
Heat transfer	6 MWe
Shuttle and Maintenance	5 MWe
Misc. power	5 MWe

Life support systems include the personal requirements of the crew members, the food production needs. Actual calculations of the power required can be found in Chapter 5.

The communications is essential to any space based system. The people on-board the Emerald City must have the ability to send and receive various messages throughout the deep expanses of the solar system. Actual calculations of required power can be found in Chapter 6.

In order to keep the Emerald City in a proper state of stability, an attitude control system is needed. This system will use a secondary propulsion system other than its main propulsion system. Some preliminary calculations have been discussed in Chapter 4.

Thermal subsystems take care of any excess heat or lack of heat the space station may require. Calculation of the power required may be found in Chapter 8.

The remaining two systems, shuttle and maintenance & miscellaneous power have estimated values of power required. The shuttle crafts may use chemical or battery oriented systems which will need recharging and maintenance. The maintenance system will be primarily robotic in nature with applications as auxiliary system maintenance and repair of the space station's outer skin. These robotic units will also be battery operated. Periodic recharging capability will therefore be needed. The remaining power will go to miscellaneous power system. The requirement of this system is also estimated and is based on a factor of safety of 25%.

7.3 POWER SOURCES

7.3.1 Power Characteristics

In determining the power source for Project WISH, there are three essential characteristics that the power system must have:

1. Abundant power capability
2. Reliability over long period of time
3. High specific power

Figure 7.1[40] presents a graph depicting possible power sources and their inherent power output and effective lifetime. There are four types of power sources shown on the graph; chemical, solar, radioisotope, and nuclear reactors.

7.3.2 Power Sources Available

A chemical power source might be able to satisfy the power requirements of the space oasis due to its large energy output. However, this type of source would have an excessive fuel requirement for the fifty plus year duration of Project WISH. To carry this amount of fuel on the space station would most likely multiply many times over the total mass of the Emerald City. This is not a desirable consequence and hence, a chemical power source was discarded.

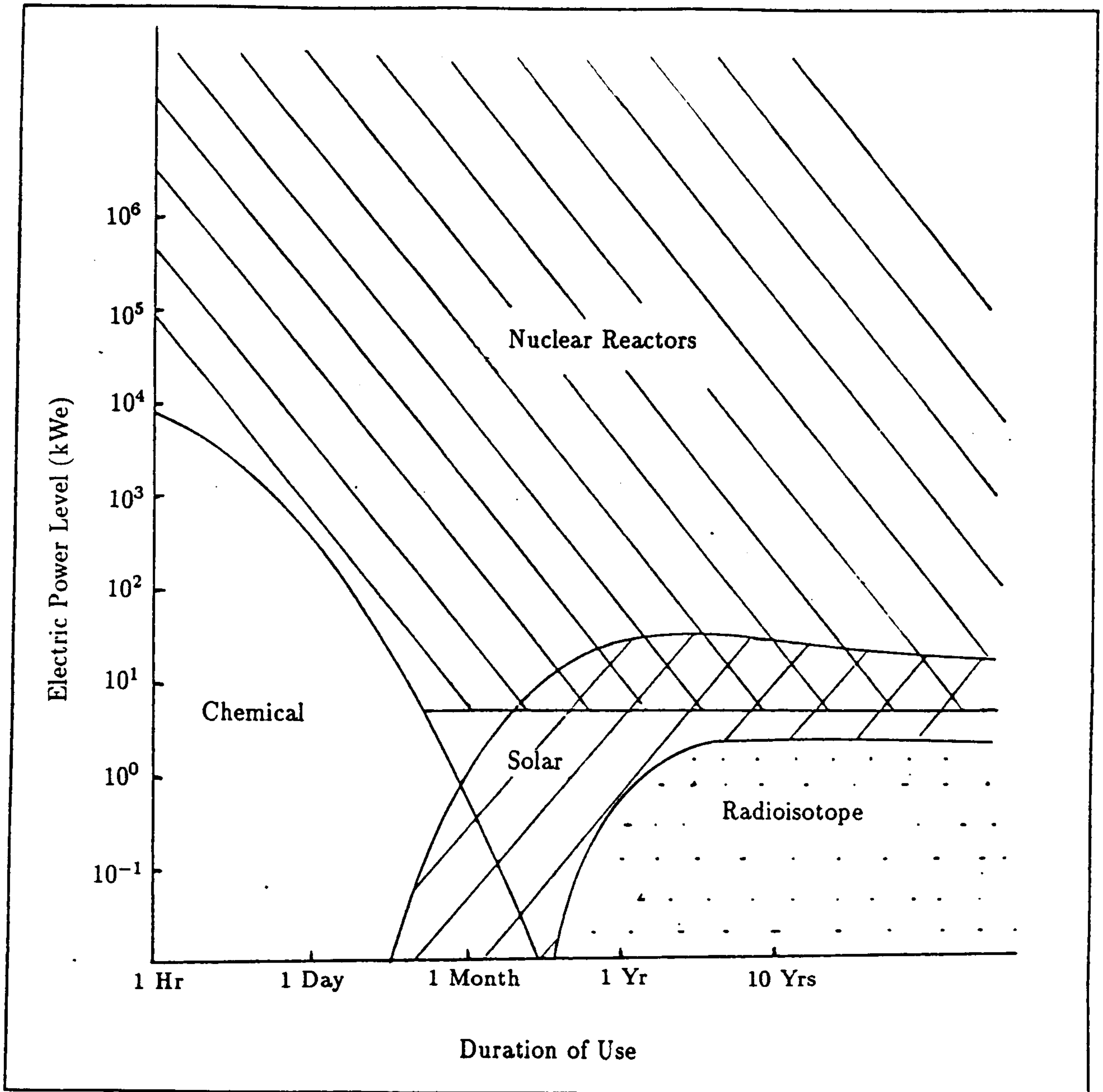

Figure 7.1: Power Sources

Solar power offers clean and relatively efficient power, but not of sufficient magnitude. In order to meet the power budget, a solar array many times the size of the space station would be required. Solar power would also limit the distance at which the Emerald City could travel from the sun. This constraint completely defeats the purpose of Project WISH. Solar power then, is also not feasible.

A third possible energy source is radioisotope decay. This method would provide very predictable amounts of power to the space station, but as with solar power, it is more applicable to low power applications. In order to generate the required power, the system would be too massive for applications such as this.

Nuclear reactors are the remaining power source possibility and can be divided into two types; fission and fusion.

In the following sections, a detailed analysis of both types of nuclear power will be documented. Nuclear power is also discussed in Chapter 3 under consideration for nuclear propulsion.

7.3.3 Nuclear Power

Fission

The first type of nuclear energy that will be discussed is fission. Fission reactors generate thermal energy through controlled fission of heavy nuclei in a sustained neutron chain reaction. A typical reaction is

$$^{235}U + n \rightarrow {}^{236}U + \text{thermal energy}$$

where a neutron is absorbed by the Uranium-235, creating Uranium-236 and thermal energy[41].

There are several types of reactors available for the Emerald City, the most advanced being[4] the solid core, gaseous core, distributed core, fixed particle bed, and rotating particle bed reactors.

The solid core reactor has its fuel in a solid form, while coolant is pumped through the core around the fuel. The latest in solid core technology is the SP-100. This reactor, however, can only be scaled up to about 1 MW(e) with its present design. With further scalability put into the design, the solid core might work for the Emerald City[10].

The gaseous core reactors have the potential to operate at extremely high temperatures, above 3000 K. The uranium fuel is in a gaseous form, and is incorporated into the working fluid. This concept is still rather new, and the reactor has only been developed for closed-cycle conversion systems.

The distributed core is different from the solid core in that the fuel surrounds the coolant. A problem with the present design is that there is an optimal power level for the number of heat pipes that run through the fluid. After this is exceeded, about 340 pipes for 40 MW(th), the efficiency decreases, and the core reaches a temperature that the heat pipes can no longer withstand[4].

A fixed particle bed reactor has a quick start-up time, and good specific powers and power densities. The core is packed with fuel in a particulate form, with a gaseous coolant flowing through the fuel. This reactor is scalable, but to quantities that are below that of what the Emerald City needs. The rotating particle bed provides even better results for the same qualities[5].

Brookhaven National Laboratory (BNL) has designed a reactor similar to that in Figure 7.2[5]. However, the reactor that BNL has designed is used solely for thrust, with an expansion nozzle at the hot gas outlet. This nozzle can be replaced with a thermal conversion system.

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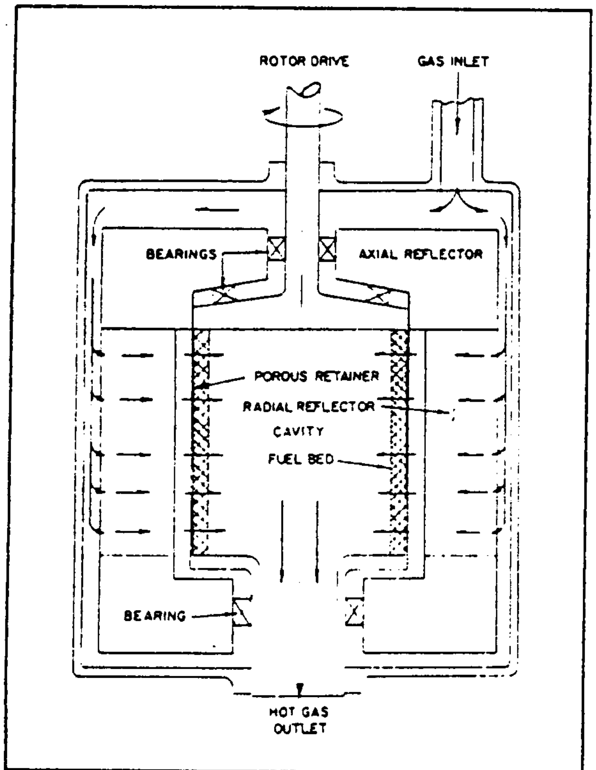

Figure 7.2: Rotating Particle Bed

The rotating particle bed operates by storing the fuel in a cylinder with porous walls. The cylinder is then rotated to force the reacting fuel against the wall for even distribution, and a cold gas is passed through the porous walls, heated, and carried out through pipes along the axis of the cylinder. Increased coolant flow rates are provided by stabilizing the fuel particles against the flow by inducing a high effective gravity field, of hundreds to thousands of g's, through rotation, thereby giving each fuel particle a very high weight[42]. The reasoning behind this is that the gas can be heated to a greater temperature because when it leaves the fuel, the gas does not have to pass through another porous wall which might be constrained by material limits. Most of the reactor can be made of modern light-weight alloys because the only extreme temperatures developed will be after the coolant passes through the fuel. This reactor is very attractive because of its quick response time, very high power density, and its virtual immunity to thermal stress.

The fuel that will most likely be used is a particulate form of UC2 (Uranium-235), surrounded by a porous layer of low-density pyrocarbon to hold in the gaseous fission products, and a coating of SiC to provide mechanical containment for the fuel. Particle diameter is of the order of .5 mm. In this form, several favorable characteristics are exhibited[5]:

1. Large surface area (100 cm^2 per cm^3) giving high heat transfer rate.
2. Small temperature difference between fuel and coolant (10K).
3. Power to full in three seconds or less.
4. No thermal shock exhibited.
5. Particles regain 99.99% of fissionable products.
6. High burn-up possible.
7. Handling of fuel is easier.
8. Good power densities (10 MW/liter of fuel).

When fully operational, there only needs to be 1 m^3 of uranium fuel to create the maximum projected output of 5000 MW(t)[43]. There are also possibilities of easier refueling of the reactor once out in space and in operation, since the fuel in particle form is easy to handle. This could help reduce the size of the reactor by a large amount.

There are two types of gaseous coolant that can be used for the rotating bed reactor to transfer the thermal energy. When large amounts of power are not needed, helium can be used in a closed-cycle loop. The gas will then transfer the thermal energy to the thermal-electric conversion system, and any waste heat can be radiated into space (see Chapter 8 on thermal systems). The helium will be used when power requirements are less than about 100MW(e), such as when no propulsion power is needed.

When the space station needs more power, hydrogen can be used in an open-cycle loop that, instead of trying to cool the hydrogen with extremely large radiators, will expel the H_2 into space after converting al. of the thermal energy needed. This can save a considerable amount of mass.

Since there are small temperature differences between the fuel and the coolant, about 10K, higher thermal energies can be transferred from the reactor to the electric conversion system. For a helium closed-cycle loop, temperatures can run from 1500-2000K . When the hydrogen open-cycle loop is used, the range of temperatures can be increased to 2000-3000 K[5].

The duality of the coolant systems make the reactor multi-functional, useful for the lower power requirements of everyday housekeeping, and the higher power burst mode the for greater power needs (possibly for the propulsion system). One problem that has to be addressed in the future is that the uranium fuel used in the hydrogen open-cycle must have a modified coating (e.g., ZrC) because the H_2 has some adverse effects on the SiC coating.

There are several quantities that are of interest to the preliminary study of Project WISH. First is the total output. The rotating particle bed reactor has a projected output of 5000 MW(t), and using a magnetohydrodynamic converter with an efficiency of 40%, can create 2000 MW(e) of power[43]. Other conversion systems, such as the Brayton and Rankine cycles, have efficiencies of 20-30%, giving electrical outputs of 1000-1500 MW(e). Conversion systems will be discussed in more detail in Section 7.4 on Power Conversion.

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The specific power is an important design parameter that gives a ratio of power to mass of the reactor. The rotating bed has projected specific powers in the range of 1 MW(t)/kg and 400 kW(e)/kg. These are extremely impressive results when compared to the massive structure of the fusion reactor of similar output discussed in the subsequent section on fusion.

By dividing the total output by the specific power, the mass of the reactor is found to be 5000 kg. In order to get mass estimates of the other components of the reactor, which have yet to be specifically determined, a linear relationship was developed using the known masses from an SP-100 reactor (see Table 7.2). The SP-100 is currently undergoing development to produce 100-1000 kW(e) of power, and is the bulk of space nuclear technology at this time. If the relationship is developed by comparing the two reactor masses, the following figures are obtained in Table 7.3.

Table 7.2: SP-100 Mass Summary

reactor	450 kg
shield	790 kg
heat pipes	460 kg
conversion	290 kg
power control systems	130 kg
supporting structure	300 kg
total	2420 kg

Table 7.3: Rotating Bed Mass Estimates

reactor	5000 kg
shield (immediate)	8778 kg
heat pipes	5111 kg
conversion	3222 kg
power control systems	1444 kg
structure	3333 kg
total	26888 kg

The shielding mass is assumed to be that which is only in the immediate surroundings of the reactor. More shielding around the actual reactor and fuel will mean less shielding needed around the work-station of the power system needed to protect the inhabitants of the Emerald City. This means less mass. More work must be done on reactor design to more accurately identify the masses of these components.

Once the nuclear thermal power is produced, a system or combination of systems is needed to convert some or all of the thermal energy into electric power. The magnetohydrodynamic power conversion system has been identified for use with the rotating particle bed at this time. A description of this and other conversion systems can be found in Section 7.4.

Some problems that need to be addressed are those concerning the uranium and the effects on the inhabitants. An adequate storage facility must be developed to hold some or all of the fuel that will be needed during the lifetime of the Emerald City. Up to 10000 kg of fuel might be needed during the lifetime of the station. A system of refueling must also be developed, and ways of manufacturing the particulate form of the fuel must be studied.

The safety to the environment of the solar system should not be forgotten. The particle bed reactors have achieved the safety specified for the SP-100 project at this point. Some of the more important requirements for an earth environment launch are listed below[5].

1. Launch problems cannot cause criticality.
2. Reactor must stay subcritical if it becomes immersed in any fluid.

3. Reactor will not operate until positioned in a stable orbit.
4. Reactor must have the capability to raise itself from any low orbit.
5. Reactor must have two separate shutdown systems.
6. Unirradiated fuel must pose no environmental problems (such as Uranium-235).

Other requirements will have to be developed for interplanetary travel as well, due to possible emission of radioactive materials.

Fusion

A fusion reactor has the potential of supplying an essentially inexhaustible source of energy for the future. Under the right conditions, low atomic number elements can react to convert mass to energy ($E=mc^2$) via nuclear fusion. For example, the fusion of deuterium (D) and tritium (T) yields four (4) helium (He) plus one neutron (n) and 17.6 MeV of energy or

$$D + T \rightarrow {}^4He + n + 17.6 \text{ MeV}$$

In order for a fusion reaction to take place the two nuclei (D+T) must have enough energy to overcome the repulsive Coulomb force acting between the nuclei and approach each other sufficiently close that the short-range attractive nuclear force becomes dominant. To obtain the required energy, the fusion fuel must be heated to very high temperatures. At this temperature, the gas exists as a macroscopically neutral collection of ions and unbound electrons called a plasma. For example, for a typical plasma, the temperature and pressure are 1.2×10^8 K and 3.2 atm, respectively. A fusion reactor, therefore, is a device which contains the fusion reaction and generates thermal power.

There are many different types of reactor design configurations currently being tested. However, the Tokamak concept which was invented in the USSR in the 1960's, is the most extensively considered. The considerable amount of investigation and consequently data available is the primary reason for considering the Tokamak concept for a power system.

The Tokamak concept, shown in Figure 7.3[44], is in the shape of a torus thus allowing a convenient way to enable the toroidal field to contain the plasma. However, due to the curvature of the toroidal field, there exist forces which act upon the charged particles to produce "drift" motions that are radially outward, which would, if uncompensated, cause the particles to impact the wall. Therefore, a poloidal magnetic field must be superimposed upon the toroidal magnetic field in order to compensate for these drifts, resulting in a helical magnetic field which is entirely

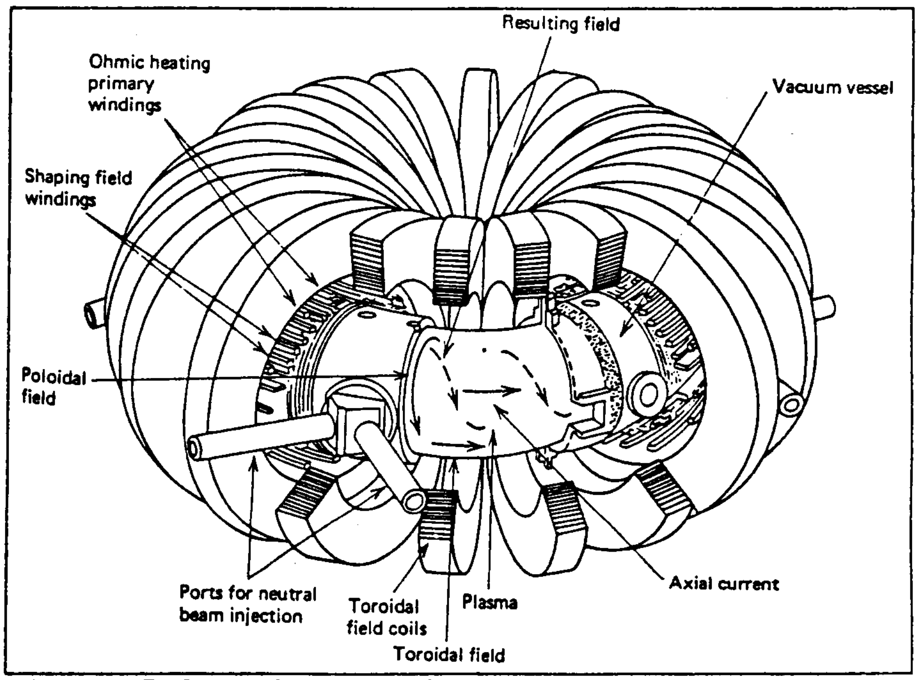

Figure 7.3: Tokamak Schematic

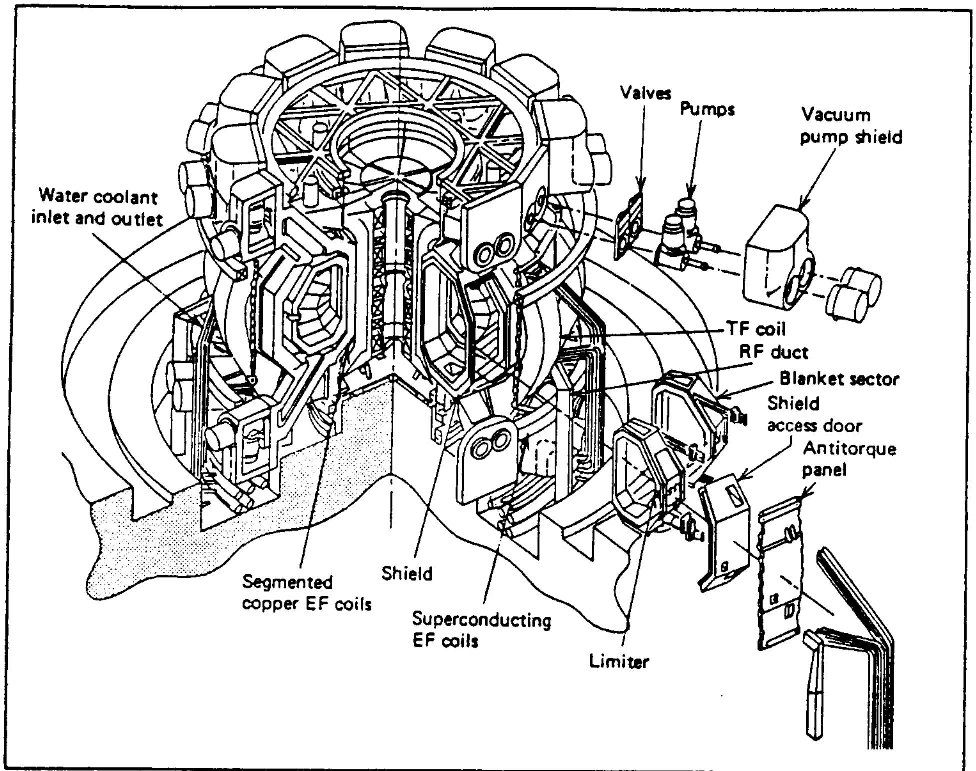

Figure 7.4: Starfire Concept

contained within the confinement chamber. An example of a Tokamak reactor is the Starfire reactor illustrated by Figure 7.4[44].

This reactor is under study by Argonne National Laboratory. Of the many different reactors to date (ie. Nuwak, Culham IIC, Sptr-P, Intor, etc.) the Starfire reactor has one of the highest gross thermal power estimates as seen in Table 7.4[44].

This reactor has a mass of 25000 metric tons (which includes the core, shielding, coils, pumps, heating units, energy storage devices etc.), a volume of 8000 cubic meters, and a mass-power density ratio of 50kW/metric ton which can deliver 1.2 GW electric power[45]. Additional key parameters, for Starfire, can be found in Table 7.5[45].

Today's technology is constantly improving. New methods of power conversion are raising the power output of fusion reactors. For example, another reactor under study by Argonne National Laboratory is Aries. This reactor is estimated to have a mass-power density ratio of 100KW/metric ton[45].

Table 7.4: Design Parameters for Fusion Reactors

Design Parameter	NUWMAK (U.S., 1979)	Culham IIC (U.K., 1979)	STARFIRE (U.S., 1980)	SPTR-P (Japan, 1981)
Major plasma radius (m)	5.1	7.8	7.0	6.8
Minor plasma radius (m)	1.13	2.0	1.94	2.0
Plasma elongation	1.64	1.68	1.6	1.6
Gross thermal power (MW)	2100	1825	4000	3700
Neutron wall loading (MW/m^2)	4.0	1.5	3.6	3.3
Plasma current (MA)	7.2	11.0	10.1	16.4
Average toroidal β (%)	6.5	7.7	6.7	7.0
Burn pulse length (sec)	225	27	"Continuous"	"Continuous"
Plasma current drive[a]	None	None	rf	rf
	—	—	90 MW, 1.7 GHz	80 MW
Plasma heating[a]	rf	NBI	rf	rf
	80 MW, 92 MHz	86 MW	90 MW, 1.7 GHz	
Toroidal field (T)	12	>8	11	12
Impurity control method	Gas blanket	None	Pumped limiter	Pumped limiter
Structural material/coolant	Ti-Al-V/H_2O	SS/He	SS/H_2O	SS/H_2O
Blanket breeding material	$Li_{62}Pb_{38}$	Li compound	$LiAlO_2$	Li_2O

In the following sections, the feasibility, some major systems, and some of the problems of building a fusion reactor will be discussed to acknowledge the complexity of fusion reactors.

Table 7.5: Key Parameters for the Starfire Fusion Reactor

Net electric power (MW)	1200
Gross electric power (MW)	1440
Fusion power (MW)	3510
Thermal power (MW)	4000
Gross turbine cycle efficiency (%)	35.7
Overall availability (%)	75
Major radius (m)	7
Plasma half-width (m)	1.94
Plasma elongation (b/a)	1.6
Toroidal field (TF) on axis (T)	5.8
Maximum toroidal field (T)	11.1
Number of TF coils	12
Plasma burn mode	continuous

In today's state-of-art, confinement is a major problem. Since the magnetic field is not perfect, there are high velocity ions that will eventually impact the confinement wall. Attempts have been made to strengthen the magnetic field to keep these ions from impacting the surface. However, a major problem arises when the magnetic field is strengthened: it compresses and heats the plasma thus causing ions to escape the field. It can be hypothesized that the larger the reactor, the easier it is to control. Compression is not a major issue.

Another problem is plasma-wall interaction. As previously mentioned, when the energetic ions reach the wall they will transfer their energy to the lattice atoms which, in turn, will collide with others resulting in atoms leaving the surface. One way to reduce this interaction is to insulate the wall from the plasma by a region of high density "cold" neutron gas.

Next, we will discuss the heating of the plasma. Plasma temperatures in the lower range of the thermonuclear regime have been achieved in Tokamaks by injecting highly energetic particles produced by an accelerator (a method called neutral beam injecting (NBI) heating). This method, takes the hydrogen or deuterium atoms (which must be neutral in order to pass the magnetic field) and injects them into the plasma. Here they become ions and give up their energy to the plasma via Coulomb scattering. Obviously, this is not the only way to heat the plasma: other methods (not as tested as much as NBI) are as follows: a) radio-frequency electromagnetic waves, b) wave heating and c) fusion alpha heating (when the plasma is raised to a certain temperature, this device uses the 3.5 MeV alpha particles produced by the fusion reaction to constitute a self-heating mechanism). The Ohmic-field-coil power supply parameters can be found in reference (46).

Energy storage system demands are met primarily by inertial and inductive systems. Since the fusion reactor requires large amounts of energy, the requirements upon the energy storage system are characterized by the total energy to be transferred, the energy transfer time, and the nature of the load (ie., inductive, resistive). Energy storage requirements of fusion will be met primarily by inertial systems (in the near future) and some use of capacitive systems.

The inertial energy storage and transfer system uses flywheels to store the inertial energy. These flywheels can be charged up with a motor, which draws power from the plant output, to high rotation speeds. At these high speeds, an electric generator is connected to produce a pulse of electric current, and in the process decreasing the rotation speed (converting the inertial energy into electric energy). Flywheels rotating at high speeds can store inertial energy densities up to several hundred MJ per cubic meter. A widely used storage and transfer system is the Motor-Generated-Flywheel (MGF) which can be found in reference (40). However, because flywheels will introduce additional undesirable gyroscopic effects to the dynamics of the Emerald City, which will already have a steady spin rate for artificial g, this inertial storage system would not be desirable.

Another energy storage system is the inductive system. Here, energy can be stored inductively in electromagnets where the energy is transferred from the fusion device coil back into the coil at the end of the cycle. Some common features of the Energy storage system for pulsed power can be found in reference (44).

The next major system is the fuel system. As mentioned earlier, the reaction used is the fusion of tritium and deuterium. Even though there are different reactions to choose from, the tritium and deuterium reaction occurs much more readily at a lower "kindling" temperature than fusion reactions of other hydrogen isotopes. Therefore, it can be concluded that a) this reaction needs less power to heat the plasma and b) confinement and plasma-wall interaction will be less.

Since tritium is an isotope of hydrogen, with a half-life of 12.3 years and a market value of $10,000 per gram, the fuel system must be very efficient[47]. Containment, therefore, is a major issue since tritium can diffuse rapidly through most materials at elevated temperatures. Additionally, the tritium fuel cycle system must recover the tritium from the exhaust gas that is pumped from the plasma and from the breeding blanket. The system must process this tritium so that it can be introduced back into the plasma chamber to fuel the reactor. This refueling is done automatically with addition by gas puffing. Reference Starfire tritium and deuterium mass flow rates can be found in Table 7.6[46].

Table 7.6: Tritium and Deuterium Mass Flow Rates

Tritium mass flow rates (g/d)	
Tritium burn-up	536
Tritium fueled	1296
Tritium exhausted	760
Tritium bred	562
Deuterium mass flow rates (g/d)	
Deuterium burned	360
Deuterium fueled	865

The largest feature of the fuel system is a device known as the blanket which surrounds the plasma chamber. The main functions of the blanket are as follows: a)- converts the fusion energy into heat and b) to produce tritium. The blanket consists of a lithium-containing tritium material, a coolant to remove the neutron-deposited heat, a structural material, and other materials such as neutron multipliers to enhance the tritium production. A fusion reactor operating on the deuterium - tritium cycle can produce a large amount of neutrons. With a modest amount of neutron multiplication, a fusion reactor should be capable of breeding enough tritium for self- sufficiency and have excess neutrons to produce fissile fuel. For example, one fusion-fission hybrid reactor producing 1000MW fusion power could support 5.7 - 3.7 1000 MW light water fission reactors[44].

The vacuum system must be able to bring the pressure in the plasma chamber (typically several hundred cubic meters in volume) down to approximately 10^{-7} torr or 1.3×10^{-10} atm. Also, the pressure in the ducts and cavities in the NBI system (typically with volumes of several tens of cubic meters) must be maintained at 10^{-7} torr. The Vacuum System must also be protected from nuclear and plasma radiation heating in order to operate effectively. Different vacuum systems (Earth based) can be found in reference (44).

The cryogenic system is a central system that supplies the required quantities of liquid helium and liquid nitrogen to the required locations near the reactor. Cryogenic refrigeration is accomplished at two temperature levels. The first is at 80 K, where liquid nitrogen is vaporized for use in thermal shielding of the liquid-helium-cooled components and pre-cooling of warm helium in the helium refrigerator-liquefier. The nitrogen is then returned to the closed cycle nitrogen liquefaction plant where it is recycled. The second level of refrigeration is at 4.2 K. Here liquid helium is pumped through the liquid-nitrogen-shielded vacuum jacketed transfer lines to its destination. The liquid helium is then vaporized and returned to where it can be recycled. The major parameters of the cryogenic system can be found in reference (46).

Another major system is radiation shielding. The purpose of the radiation shielding is to attenuate the neutron and gamma radiation in order to limit radiation damage and nuclear heating of sensitive components to a level that will admit personnel access. The blanket, which surrounds the plasma chamber, acts as a shield in removing 99% of the neutron energy and in attenuating the incident neutron flux by a few orders of magnitude. The blanket is next surrounded by a bulk shield which attenuates the neutron and gamma fluxes tc an acceptable level. Finally, the wall of the reactor acts as a "biological" shield.

Today's fusion reactors require a tremendous amount of power. Large quantities of electric energy are required in the operation of pulse electromagnets, required heating systems (ie., NBI), cryogenic systems, vacuum systems, tritium system, etc. Total power requirements can be achieved by: a) controlled pulsed demands for very large amounts of power for short periods of time, b) recovery of the inductive energy in the coil system during shut down. Fusion devices employ energy storage systems which provide large pulsed power demands and can accept the pulsed energy loads from the coils. These storage systems can draw power continuously from the electric power output of the plant. The continuous electric power requirements for a Tokamak engineering test reactor (ETR) is shown is Table 7.7[44].

Table 7.7: Load Description for Tokamak Test Reactor

Load Description	Estimated Power (MW)
Energy storage system (MGF)	80
All coolant pumps	20
Cryogenic systems	45
Vacuum systems	5
Auxiliary heating (steady-state)	15
Tritium system	5
Burn power supplies	15
Facility power (HVAC, lighting, etc.)	15
TOTAL	200

In Table 7.8[44], the start up and shut down energy requirements can be found. As mentioned earlier, the power required to start or shut down a reactor needs to be pulsed.

Table 7.8: Pulsed Load Requirement

Start-up		
	Energy	13.7 GJ
	Peak load	3.6 GW
Shut down		
	Energy	7.0 GJ
	Peak load	2.4 GW

In conclusion, the reactor delivers 4000 MWth to the power conversion system which generates 1440 MWe. A circulating load of 240 MWe results in 1200 MWe of power deliverable to the grid (see Figure 7.5[46]).

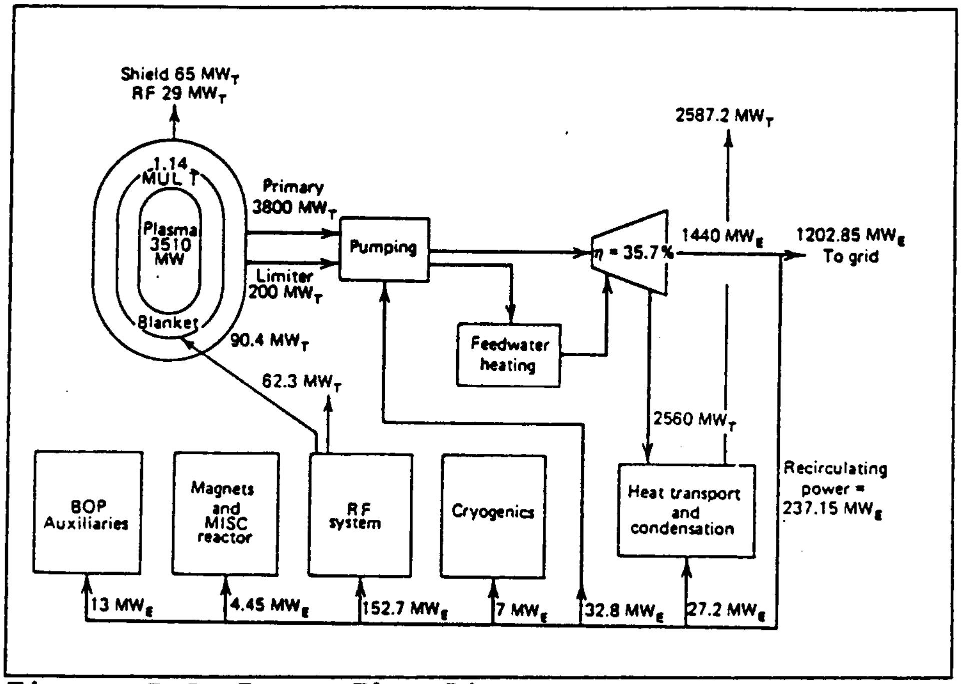

Figure 7.5: Power Flow Diagram

Comparison of Fission and Fusion Power Systems

If the power required for the Emerald City does not rise into the terrawatt range, the reactor used will be the rotating particle bed reactor based on mass, specific power, and scalability considerations. However, if the power budget does go into the terrawatt range, a fusion reactor would then be needed since these reactors have the potential of supplying an essentially inexhaustable source of energy. In this case, the considerations of mass, and specific power will not be as important as the total power achieveable.

Table 7.9: Comparison of Fusion and Fission Reactors

	Rotating bed	Fusion
Thermal power (MWth)	5000	4000
Electric power (MWe)	2000	1440
Specific power (kWe/kg)	400	.05
Mass of reactor system (kg)	26888	25×10^6
Volume (m^3)	1500	8000

Fusion safety aspects are improved when compared to fission reactors. Safety aspects are as follows: a) problems of accidental criticality and of prompt criticality are not applicable, b) Prospects and consequences of a loss of coolant accident are less, c)biological hazards of radioisotopes in the plant are lower, d) radioactive-waste-storage requirements will be less complicated owing to the absence of fission products and actinides and e) low-level-radioactive-waste production is less. Maintaining a fusion reactor will require 1-3 major shutdowns per year due to component failure (based on today's technology). Provisions, of coarse, must be incorporated for replacement and for emergency power. For example, during shutdown, an alternative power source must be supplied. Estimated lifetime for a fusion reactor is based on the magnet system used and shield, a typical fusion reactor will have a normal operating life time of about 40 years.

7.4 POWER CONVERSION

The thermal energy generated by the nuclear reactors must be somehow converted to electric energy. Thermal energy conversion can be accomplished in a variety of ways. These techniques can be divided into two general categories, static and dynamic (see Figure 7.6).

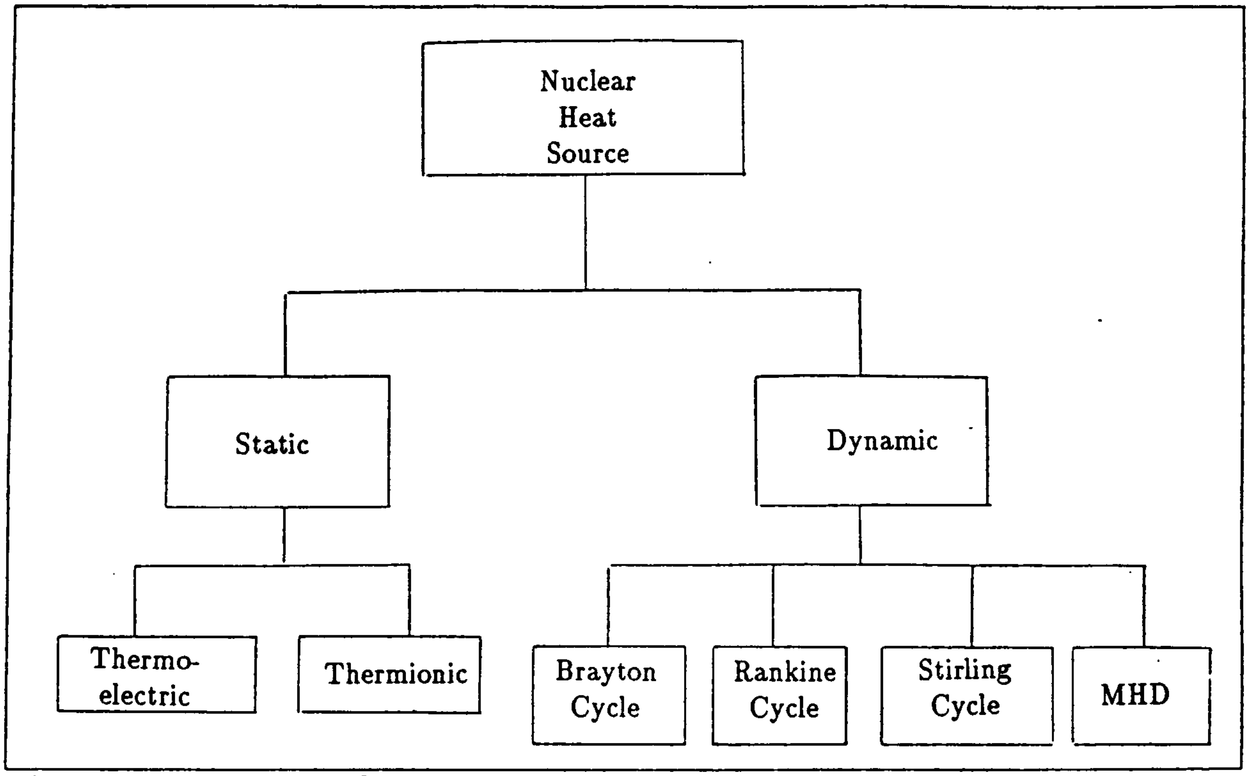

Figure 7.6: Thermal Energy Conversion

Static energy conversion techniques use thermophysical principles that require no moving mechanical parts. Examples of this type of energy conversion system are thermoelectrics and thermionics.

Thermoelectric devices are based on the Seebeck Effect in which two dissimilar materials are maintained at different temperatures, forming the basis of a thermocouple. The juncture of the two materials generates an electromotive force or electric potential. This electric potential can then be used to drive a current.

Thermionic devices are essentially a hot emitter surface separated from a cool collector surface by an interelectrode gap. Electrons are boiled off the hot emitter surface and captured by the cooler collector surface creating a voltage potential. These static conversion techniques are more suited to low power (1 kW to 100 MW), short duration (<

10 yrs.) type missions and are not feasible for the Emerald City's mission[48].

Dynamic systems however, offer the ability to convert large amounts of thermal energy to electric power with good reliability and for long periods of time.

These dynamic systems use the heat engine principle to provide the mechanical work necessary to generate the electric energy in a turbo-machinery assembly. There are three types of dynamic systems:

1. Rotating machinery (Brayton and Rankine cycle)
2. Reciprocating machinery (Stirling engine)
3. Advanced concepts (Magnetohydrodynamics)

The Brayton cycle uses a gas as its working fluid in a turbine/-compressor configuration to turn an alternator, producing electric power. With an inlet temperature to the turbine of 1300 K, conversion efficiencies can reach near 25 percent. One problem with this system is that using a gas as the working fluid makes for a more massive system which uses a two phase working fluid such as a Rankine cycle power converter[48].

Rankine cycle systems use a two phase working fluid as described above in a turbine/generator assembly. The best choice for a working fluid would be an alkaline metal such as rubidium, potassium, or sodium. The working fluid is first boiled via a heat exchange with the thermal energy produced by the reactor. The vapor then drives the turbine before being condensed back into liquid form. With a wet vapor temperature of 1400 K, conversion efficiencies of 20-25 % can be attained[48].

A Stirling cycles system known as the Free Piston Stirling Engine (FPSE) uses two opposing pistons in a common cylinder to achieve efficiencies approaching 30 percent[48]. What makes this system so efficient is that it achieves almost total heat reversal. That is, energy transfer both to and from the system occurs both isothermally and reversibly. This is accomplished through the use of regenerators that alternately store and then recover the heat. Since the regenerator is in exactly the same state at the end of the cycle as it was in the beginning, it is considered part of the heat engine and not as an external source or sink. There is a problem with using this type of power converter, and that is scaling ability. At the present time, 150 kW per module is the highest output level available, far below what is needed for Project WISH.

Finally, there is the Magnetohydrodynamic (MHD) power conversion system. This device is based on the concept that if a metal conductor is rotated in a magnetic field, an electric potential can be produced. The MHD takes this concept one step further and replaces the metal conductor with a conducting gas. The MHD achieves high efficiencies if two criteria are met:

1. The gas must be accelerated to very high speeds through the magnetic field.
2. The gas must have a very high temperature (2500K).

To accomplish these tasks, a turbine is coupled to the MHD, forming what is known as the Turbo-MHD. If ceramic technology can produce a turbine blade which can withstand 2500 K temperatures, this system can reach efficiencies of up to 40 %[49]. This device has an earth weight of 200-500 tons[50].

In conclusion, the MHD conversion system will be the primary conversion system for the Emerald City, due to the high efficiencies. Thermoelectrics will be the secondary system used for everyday housekeeping, because there are no moving parts, and is less likely to break down than dynamic systems (see Figure 7.7).

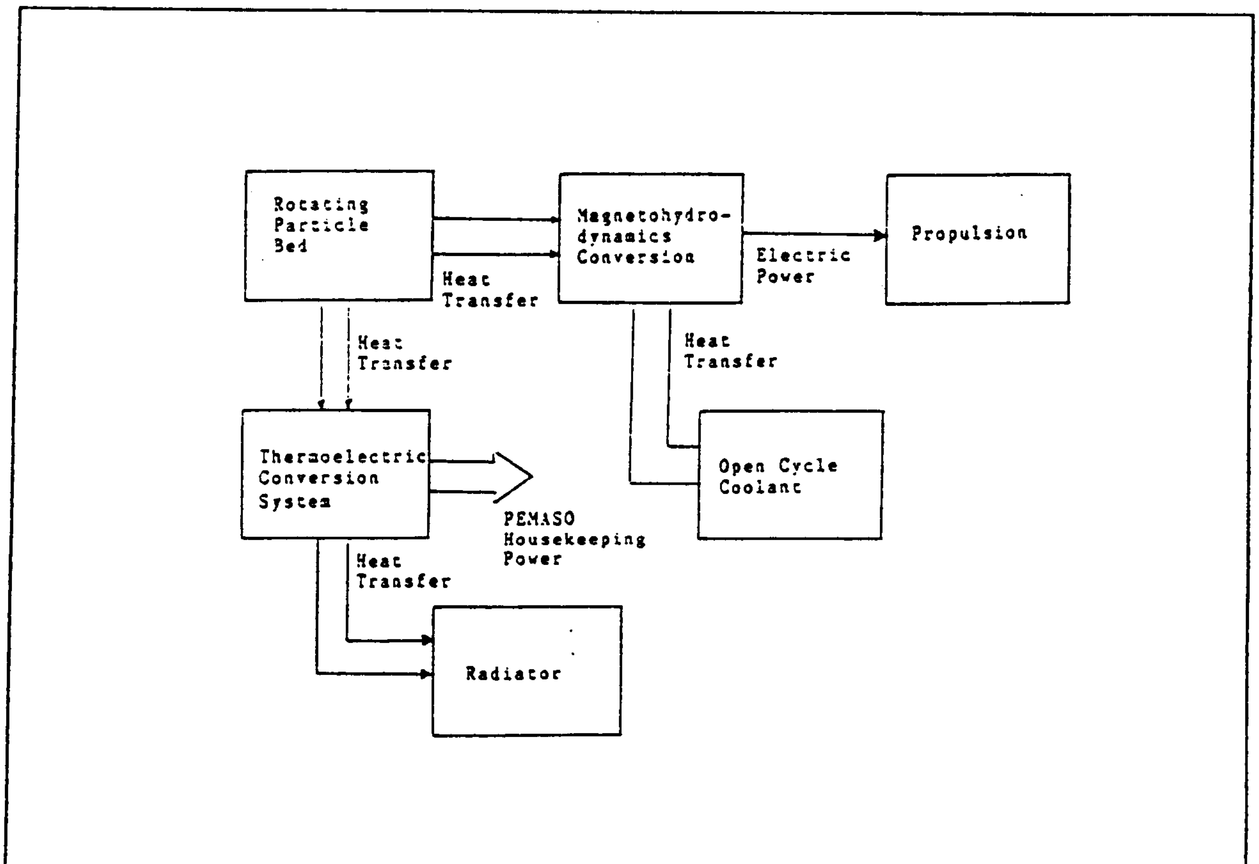

Figure 7.7: Schematic Diagram of Multi-Mode Reactor System for the Emerald City

7.5 CONCLUSION

The Emerald City will use a rotating particle bed fission reactor, with the Magnetohydrodynamic (MHD) power converter as its primary conversion system. A secondary power converter, used for house keeping, will be the thermoelectric power converter.

CHAPTER 8

THERMAL SYSTEM

8.0 INTRODUCTION

The thermal control subsystem for the Emerald City consists of two parts: (1) the active thermal radiator to dissipate the waste heat and (2) the thermal analysis and model of the spacecraft. First, six types of radiators are described. Then a detailed description of the candidates for the Emerald City are discussed. The design specifications are also listed. Then, a thermal analysis and model, including equations, is described for the space station. The analysis includes thermal factors such as coatings, insulations, and interaction between equipment and people. The model uses a simple heat exchange equation to estimate the temperature of the spacecraft.

8.1 ACTIVE THERMAL CONTROL RADIATORS

There are two ways to dissipate the waste heat generated by the Emerald City: (1) to reject the heat as a form of mass and jettison it overboard and (2) to emit the energy as a form of thermal radiation. The Emerald City will use radiators to emit the waste heat because a mass conversion system is too heavy. Several criteria must be considered when selecting a radiator: external environment, amount of waste heat, radiator surface area, circulating fluid system, and micrometeoroid protection. Ideally, the radiator must not depend on surface area while minimizing the mass.

8.1.1 Thermal Radiators

Six thermal radiators are available that provide the above requirements: the modular wide heat load fluid radiator, the self contained heat rejection module, the flexible deployable space radiator, the modular heat pipe radiator, the liquid droplet radiator, and the rotating bubble membrane radiator.

The modular wide heat load radiator varies the flow of the radiating fluid to control the heat load present. There is a fixed area exposed to space and the maximum heat rejected is dependent upon this area. However, for a low load, either a refrigeration unit is used or the radiator must operate at a temperature below the system rejecting the waste heat. The radiator uses a stagnation control method which controls the freezing and thawing of the radiator fluid to control the heat loads of the system.

The self-contained heat rejection module accommodates a wide variation of heat loads and temperatures. It contains equipment necessary to reject heat in orbital environments. A dual-system approach is used to provide heat rejection for nominal and extreme load requirements. Fluid swivels provide fluid transfer between the deployable panels and heat transfer from the heat source is provided by a heat exchanger.

The flexible deployable space radiator uses deployable panels made of flexible fin materials. This system can be used on existing spacecraft because it is compact and relatively damage free. Fluid is pumped through the fin and heat is radiated to space from both sides of the fin. The soft tube and the hard tube are two types of fins. Both are compact and deployable. The fluid tubing can be arranged to minimize weight in both types. However, the aluminum tubing of the hard tube fin provides better meteoroid protection.

The modular heat pipe radiator is the system currently used on manned missions. In this system, fluid is mechanically pumped through the radiator and heat is rejected to space. Modular blocks are used to accommodate the varying heat loads of the spacecraft. Although this is an inexpensive system, the mass takes a large part of the payload because the meteoroid protection is extensive[51].

The liquid droplet radiator (LDR) uses nozzles to spray molten metal onto a collector. As the metal droplets travel through space, they radiate the waste heat. The majority of the mass is in the supporting structure. The mass is lower for the LDR because the tiny round droplets radiate the heat. Also, no protective covering is needed because meteoroids pass through the spray and there is a slight loss of the molten metal[52],[53].

The rotating bubble membrane radiator (RBMR) uses a two-phase working fluid and takes advantage of the high heat fluxes of the heat pipe radiator and the low mass of the LDR. In this system, molten metal is sprayed into an envelope or bubble. The droplets condense and radiate energy as they hit the bubble. By rotating the radiator, the droplets are collected in a trough by centrifugal force and recirculated[51].

8.1.2 Recommendation

The selection of the radiator depends on three factors: size, mass, and spacecraft configuration. Based on size and mass of the total system, the LDR and the RBMR are the best radiators. Both of these have considerably less mass than the other four radiators because neither needs a thick metallic meteoroid protection shield. The two radiators are also better suited for scaling up to a larger heat load produced by the spacecraft power system. The other four radiators, especially the flexible fins and the modular wide heat load radiator, would require a large surface area possibly larger than the ship.

The rotating bubble membrane radiator is a better selection than the liquid droplet radiator based on the spacecraft configuration and metal replenishment. The radiator needs to be placed near the power system housed in the cylindrical section of the spacecraft (see Chapter 9 on Configuration). By 'wrapping' the bubble around the cylinder (see Figure 8.1), it can be placed near the power system. By doing this, the motor used to rotate the bubble can be eliminated because the entire spacecraft will be rotating. Self-sealing material is used for the envelope to repair tears and prevent a loss of

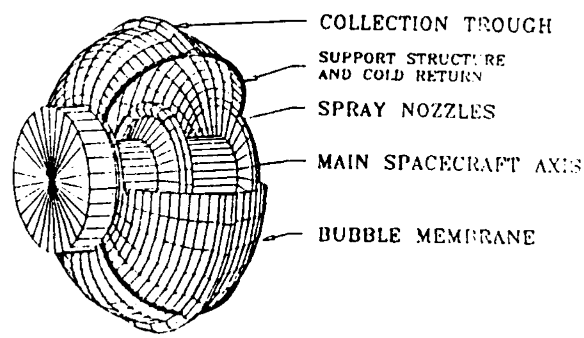

Figure 8.1: Bubble Membrane Radiator

the molten metal. In the liquid droplet radiator, the meteoroid passes through the spray and picks up some of the metal; thus, it must be equipped with a fluid storage tank.

Another problem with the liquid droplet radiator is the nozzle accuracy. To minimize the loss of metal to space, the nozzles must aim at the collector. Although the technology in the field of nozzle accuracy is improving, the bubble membrane requires no accuracy of the spray of metal because the nozzles are placed around the circumference of the spacecraft's cylinder and are enclosed within the envelope. Then, the droplets are collected in the collection trough and returned to the system by the return piping.

The surface area, A, of the envelope is a function of the waste heat, Q_r, and is found by

$$A = \frac{EQ_r}{\varepsilon\sigma(T_r^4 - T_s^4)} \tag{8.1}$$

where E is the introduced error, ϵ is the emissivity, σ is Stefan-Boltzmann constant, T_r is the radiator temperature, and T_s is the temperature of space. Equation 8.1 is used, in conjunction with the radiator surface area equation, to generate Figure 8.2. In the calculation, several parameters were assumed: E is 5% , ϵ is 0.9, and T_r is 775 K. It shows the variation of the radius of the bubble membrane, r, against the waste heat to be dissipated, Q_r. Assuming a radius of 52 meters and an envelope thickness of 0.15 mm the mass of the system is estimated at 6000 kg.

The principal reason for selecting a bubble membrane radiator is one of mass. The bubble minimizes meteoroid protection and provides a suitable surface area to dissipate the waste heat. Future work for the thermal radiator will consist of a coordination with the power system and the selection of the materials for the bubble and molten metal. Although the RBMR is relatively new and untested, the technology for such a system is possible within the time frame of Project WISH.

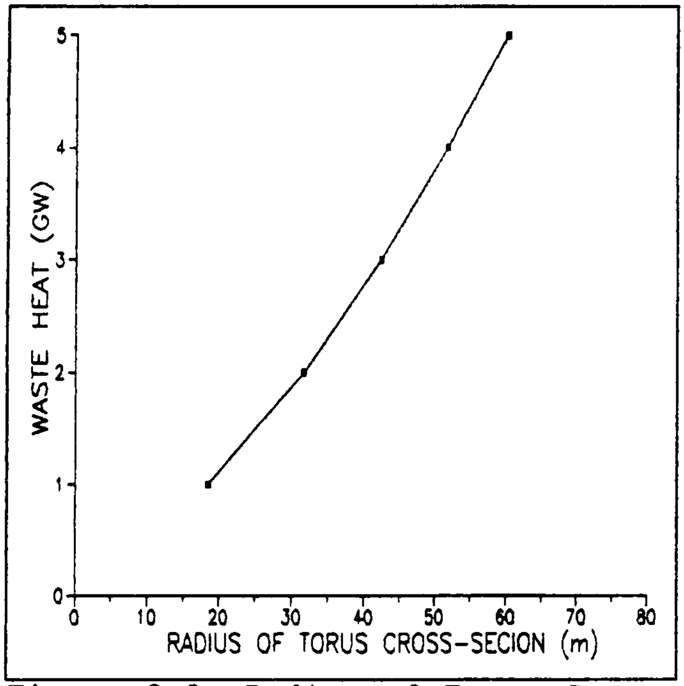

Figure 8.2: Radius of Torus Cross-section vs. Waste Heat

8.2 THERMAL ANALYSIS

A thermal analysis, including heat transfer equations, is important to the study of the Emerald City. The use of the equations mentioned will help to build a thermal model of the space station. The equations approximate the waste heat produced by people and equipment. It is important to estimate the temperature because it will have to be regulated to specified ranges for people, agriculture, and equipment.

The thermal analysis begins with a simple heat balance equation of

$$H_s = Q_{in} - Q_{out} + W_D \tag{8.2}$$

where H_s is the heat stored, W_D is the power dissipated, and Q_{in} and Q_{out} are the incoming and outgoing heat flow, respectively. For a spacecraft, the heat absorbed is the absorbed sunlight. If the spacecraft is in orbit around a planet, albedo and planet emitted radiation are also included in the heat absorbed. Heat is produced by humans and electrical and electronic equipment. Infrared radiation is rejected from the surfaces of the spacecraft. Also, there is heat exchanged among components by radiation and conduction. As an example, the temperature of a spacecraft is a direct function of the absorptivity, α_s, and emissivity, ϵ by:

$$T=\left(\frac{\alpha_s}{\varepsilon}\right)^{1/4}\left(\frac{S}{4\sigma}\right)^{1/4} \tag{8.3}$$

where S is the solar flux (W/m^2) and σ is Stefan-Boltzmann constant. This equation illustrates the difference in surface coatings on a spacecraft. Table 8.1 illustrates the use of Equation 8.3 for several surface coatings; S is assumed to be 1.3 kW/m^2 (the solar flux if the Emerald City is operating at 1 AU).

Table 8.1: Paints and Materials

	α_s	ϵ	T (K)	T (°C)
Black paint	0.9	0.9	275.1	2.1
White paint	0.2	0.6	418.2	145.2
Aluminum	0.15	0.06	346.0	73.0
Gold	0.25	0.045	422.4	149.4

For the simple case of an isothermal spacecraft, the heat balance equation becomes:

$$mc_p(\frac{dT}{dt})-Q_{in}-Q_{out}+W_D \tag{8.4}$$

where m is the total spacecraft mass, c_p is the specific heat, and T is absolute temperature. Replacing the right side with the proper equations, the heat balance equation becomes:

$$mc_p(\frac{dT}{dt})-\alpha_s S\mu_f a+P-\epsilon A\sigma T^4 \tag{8.5}$$

After rendering the left hand side of Equation 8.5, the steady state equilibrium temperature is given by:

$$T_E=\left(\frac{W_D+\alpha_s S\mu_i a}{\varepsilon A\sigma}\right)^{1/4} \tag{8.6}$$

where W_D is the equipment heat dissipated, α is the solar absorptance, S is the solar flux, μ_i is the solar aspect coefficient, a is the spacecraft surface area, ϵ is the emissivity, A is the radiator area, and σ is Stefan-Boltzmann constant. In terms of T_E, the equation becomes

$$\frac{dT}{dt}=\frac{T_E^4-T^4}{4\tau T_E^3} \tag{8.7}$$

where the thermal time constant, τ, is given by

$$\tau=\frac{mc_p}{4\varepsilon\sigma A T_E^4} \tag{8.8}$$

For the solution, an integration of Equation 8.7 is performed and two different solutions are derived depending on whether the temperature increases or decreases.

For an increase in temperature

$$\frac{t}{\tau}+C=2\left(\coth^{-1}\frac{T}{T_E}-\cot^{-1}\frac{T}{T_E}\right) \tag{8.9a}$$

For a decrease in temperature

$$\frac{t}{\tau}+C=2\left(\tanh^{-1}\frac{T}{T_E}+\tan^{-1}\frac{T}{T_E}\right) \qquad (8.9b)$$

C is a constant of integration and is found from the initial conditions of T at time t = 0. These equations are useful for a spacecraft in orbit around a planet or satellite when eclipse and non--eclipse periods are experienced by the craft. However, Equation 8.6 is used to produce Figure 8.3 which shows the change in equilibrium temperature against the solar flux encountered. As the spacecraft changes positions in orbit, the solar flux reaching the ship will change and thus, the temperature will change as well. For a nominal orbit of 12 AU, the equilibrium temperature will be about 180 K for the Emerald City.[33],[54]

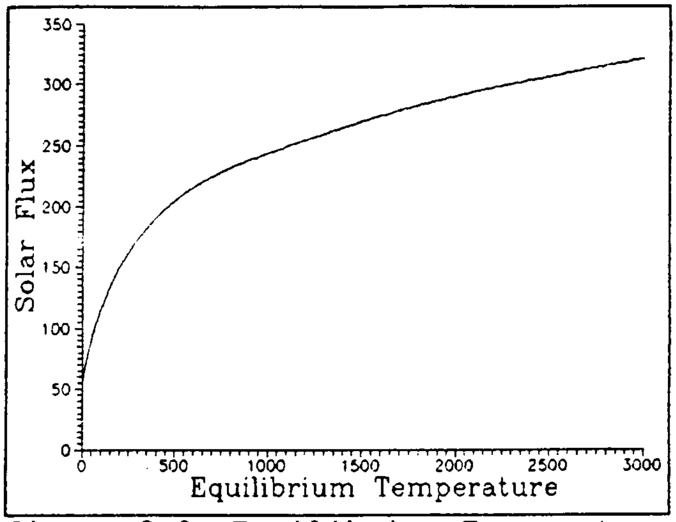

Figure 8.3: Equilibrium Temperature vs. Solar Flux

8.3 THERMAL MODEL

Although the above equations will give an approximation of the temperature and the heat transfer of the spacecraft, an analytical method must be used to obtain a better distribution of the temperatures of the real spacecraft. To obtain a better picture of the thermal transfers occurring on a spacecraft, a lumped parameter model can be used. This model no longer assumes the spacecraft is isothermal but breaks it up into n number of smaller parts or thermal nodes. Then, a variation of the heat balance equation is applied

$$m_i c_i \frac{dT_i}{dt} + \sum_{j=1}^{n} C_{ij}(T_i - T_j) + \sum_{j=1}^{n+1} \sigma R_{ij}(T_i^4 - T_j^4) = P_i + \alpha_{st} A_i \mu_i S \tag{8.10}$$

where C_{ij} is the conductive coupling between ith and jth thermal nodes and R_{ij} is the radiative coupling between the same nodes. Because the resulting heat balance equation (Equation 8.10) is non-linear, the aid of a computer is needed to calculate the temperatures by numerical techniques. The full scale study of Equation 8.10 would however have to be done in connection with the structural configuration and vehicle dynamics of Chapters 9 and 4, respectively, which will determine the materials and structural component geometry. This in turn will establish the heat coefficients C_{ij} and R_{ij} in Equation 8.10.

Future work on the thermal system will consist of a mathematical model using the above equation and one of several computer programs available. First, the design of the spacecraft configuration, its materials, and its interior design must be finalized. Once this is done, the spacecraft can be divided into nodes and, with the aid of a computer, a mathematical description of the thermal system can be obtained.

CHAPTER 9

CONFIGURATION

9.0 INTRODUCTION

A configuration for the Emerald City should take into account as much of the information provided in the previous sections as it can in order to get the overall best design possible. This chapter will deal with an initial configuration that was determined from the data presented on all of the other subsystems.

9.1 REQUIREMENTS

To determine an acceptable configuration, all of the subsystems had to be accommodated. Not only does each of the subsystems have to be in an appropriate place with respect to each other subsystem, but the entire unit has to meet the stability and control requirements. At this stage in development the requirements are very general. This configuration is a place to start rather than a final design.

The systems that need to be integrated are the shuttle(s), communications, habitat, power, thermal control and propulsion. These systems have to be pieced together in a fashion so that the stability requirements are met and construction is feasible.

The shuttle(s) will be occasionally doing docking maneuvers with the main ship. For this reason the dock should be on the main axis of rotation, preferably de-spun. The communications platform will also have to be de-spun in order to provide constant communications (see Chapter 6). The instrumentation on board the platform will have some very stringent pointing requirement, therefore the platform will have to be steady at all times.

The habitat has to protect the crew from the hazards of space. These hazards include micrometers, solar and cosmic radiation and near vacuum. The living quarters must provide 2800 kg/m^2 shielding for galactic radiation and an additional 2200 kg/m^2 for solar flares. A comfortable pressure has been determined to be 50000 N/m^2. The living quarters are also required to be spun with the occupants at an average distance of 270 meters. Besides being a protective shelter, the habitat also has to support agriculture and life support in an architecture that will avoid unnecessary stresses for its human occupants.

The propulsion system is a antimatter drive (see Chapter 3). It must be able to access the hydrogen it uses as a working fluid. This drive emits large amounts of gamma rays which are lethal to living organism if not shielded. It also emits large amounts of heat which could be used to generate electric power or it must be radiated away. The drive is inert when not in use. The power system is nuclear fission reactors (see Chapter 7). This also produces deadly radiation, and should be shielded enough to provide constant protection.

Finally the thermal control system is a bubble membrane (see Chapter 8). This system can be placed just about anywhere along the axis of rotation, but it must be rotating. It would be convenient to put it on one end of the ship to prevent the radiated heat from being reabsorbed. It would also be convenient to have the radiator close to the heat source. These heat sources are the reactor, the antimatter drive and the propellent. The propellant is not producing heat, but it must be kept cold.

9.2 DESIGN

The design is comprised of various sections roughly correlating to the subsystems. These sections include the habitat, power and propulsion, fuel tankage, radiator, de-spun platform and the connecting pieces. This configuration is pictured in Figure 9.1.

The habitat is a torus with an outside diameter of 600 meters and a tubular radius of 60 meters. The torus shape is very efficient for a pressure vessel because the entire pressure force is absorbed uniformly in tension rather than in the bending and shear stress concentrations inherent pressure vessels with sharp corners.

If this structure is made of a medium grade aluminum alloy, then the minimum thickness of the shell will correspond to radiation shielding of 3000 kg/m^2, just over the 2800 kg/m^2 required for galactic radiation. This torus also allows for the average radius of the living quarters to be 270 meters.

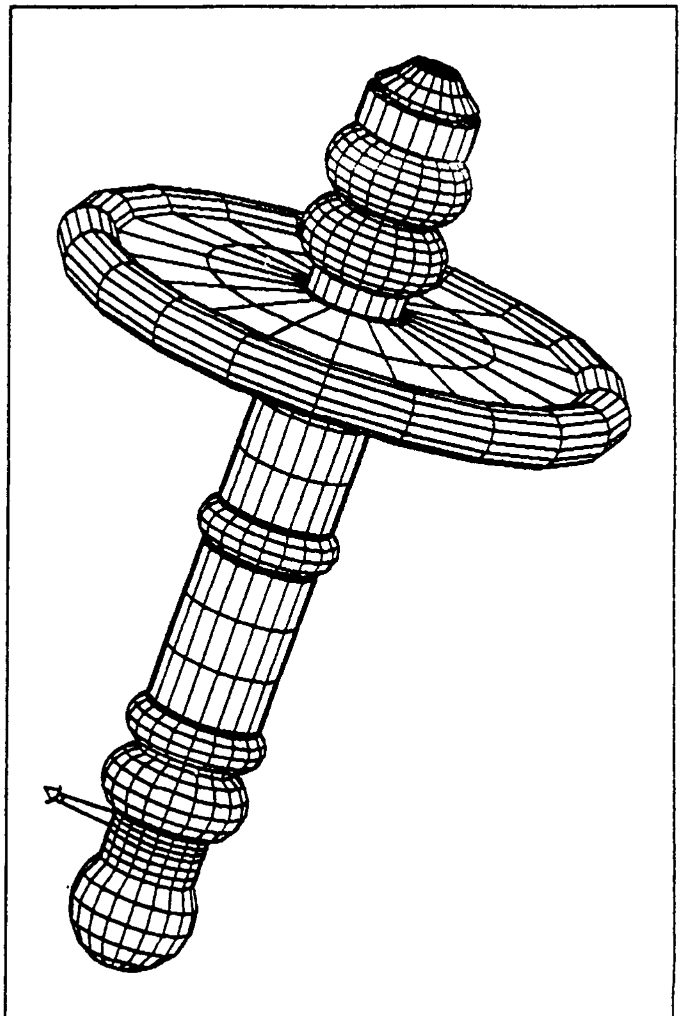

Figure 9.1: The Emerald City

Figure 9.2 shows a cross section of the torus. The interior will have three permanent levels and several temporary levels. The permanent levels will have plumbing, power, air circulation and communication capabilities. The temporary levels will be built to suit specific needs such as housing, manufacturing or life support.

The torus will also be sectioned with bulkheads. These sections will be capable of being completely sealed. This will allow sections to be quarantined for health reasons or in case of an a lethal emergency such as a rupture in the skin.

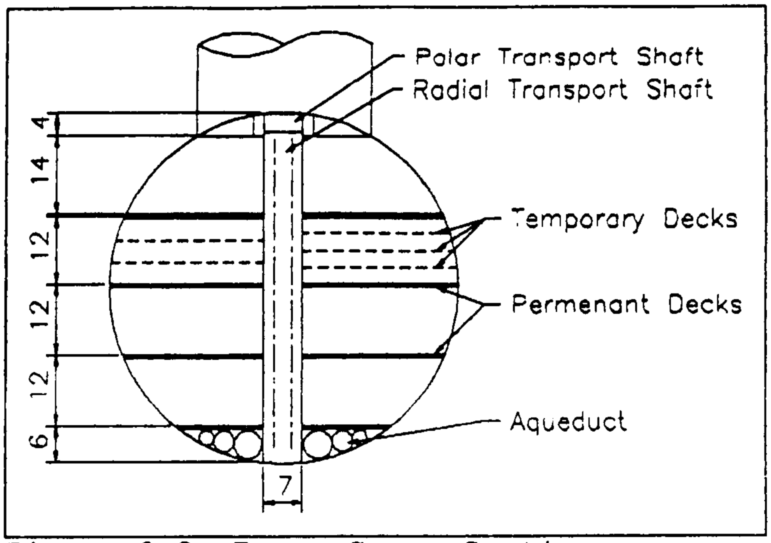

Figure 9.2: Torus Cross-Section

For psychological reasons it may be advantageous in certain sections to leave the top permanent floor completely clear. This open space is large enough for a park including small hills and open spaces for sports. This sort of section would allow people to escape the feeling of being in a closed environment. Certainly psychological effects will play a large role in the architecture. A vehicle control system was also included in the interior design. This system involves an aqueduct running through the lowest deck of the habitat. The mass moved in these ducts adjusts the ships center of gravity to compensate for any shift in mass in the ship.

The propulsion system is optimally placed on one end to provide a large gimbal angle (35 to 40 degrees). Also it is advantageous to transfer all of the force through the axis. The main coil which provides the magnetic nozzle for the antimatter drive also protects the habitat

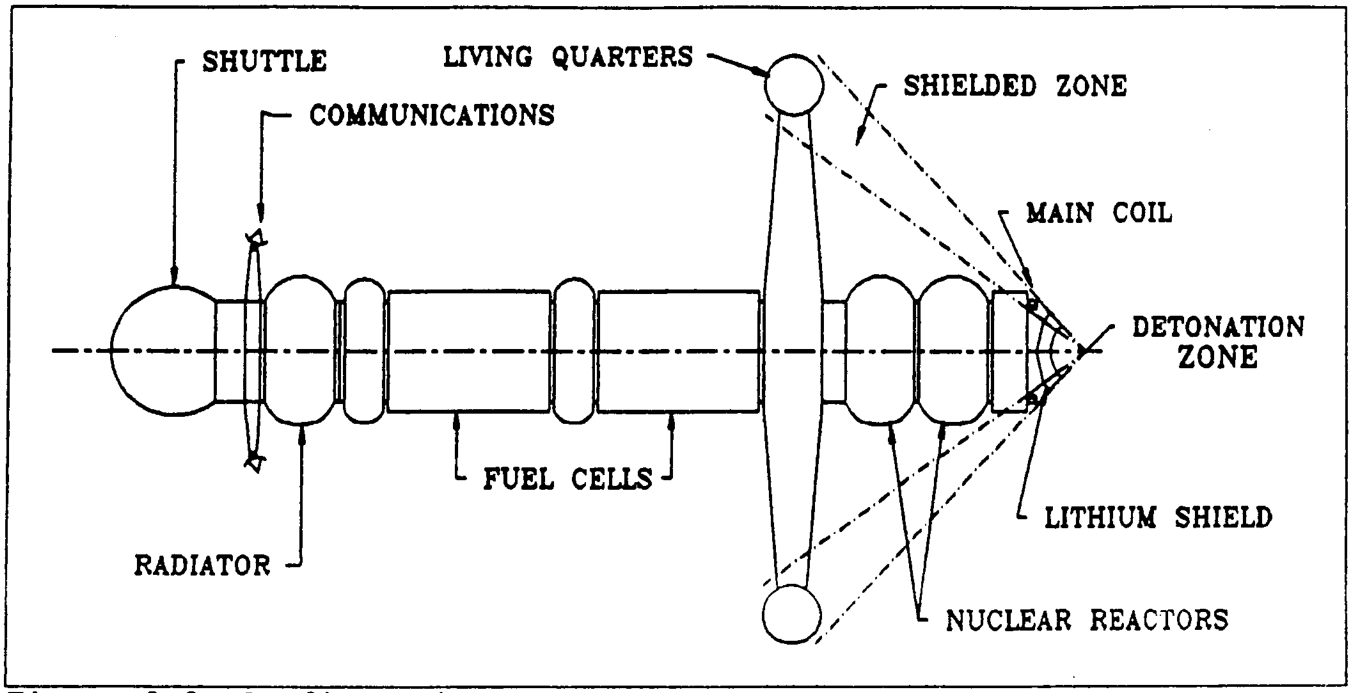

Figure 9.3: Configuration

from the large amounts of gamma radiation produced by the antimatter drive (Figure 9.3). The nuclear power system will have to be shielded sufficiently to provide protection for the crew and all close proximity maneuvers. It should also be capable of an unassisted orbital reentry, in cases of emergency. Each reactor will be able to be independently jettisoned.

Fuel tankage is the major weight component. Since this is our major limitation for trip distance it is convenient to modularize this section. Adding more fuel tanks should not significantly change the analysis of the ship. Each set of fuel tanks are connected to a main load carrying structure. The closer the tanks are to the propulsion system the larger the support structure will need to be. Each fuel section will also have plumbing for the fuel, power transmission, heat pipe and communication capabilities.

The main radiator relies on the ship spinning. This requires that it be placed around the axis. This system can be placed on the end of the fuel tanks. The fuel can be used to keep the antimatter drive cool and the radiator is used to keep the fuel cold. Heat from the other systems needing to be cooled will have to be transferred to the radiator by means of heat pipes.

On the very end will be the de-spun section containing the shuttle(s) and the communications platform. The connections between the de-spun and spun sections are mechanical, power, fuel and personnel transport. These sort of connections are not complex and can be produced very reliably. The shuttle(s) will benefit from this placement because it is easier to dock a non-spinning object. The communication platform will benefit from the shuttles larger inertia, which will help steady the platform. Also the communication system will have a large degree of visibility range. The shuttle, communications platform and the radiator are all relatively light weight, therefore their placement far from the propulsion system is not important.

The main support structure that runs through the fuel cells will connect directly to the radiator. This structure will also run through the nuclear reactor and connect to the propulsion system. Although the structure could be made out of any strong material, It may be advantageous to construct it out of concrete. This material has a very large compressive strength to weight ratio.

The torus will be connected to the main structure with a large number of spokes, similar to a bicycle wheel. There will also be two pressurized tubes connecting the habitat with similar tubes in the main structure. These tubes will be the means of transportation between the habitat and the shuttle.

CHAPTER 10

PROJECT SUMMARY

Project WISH is a continuing, three-year project. The work detailed in this report was the result of the first year of effort, with no previous design to go on. Thus, much of the time was spent just defining the problems facing Project WISH before any of the actual design could begin. The purpose of this year's parametric studies was to determine the requirements for orbital mechanics, power and propulsion systems as they are related to each other and other subsystems such as life support, communications, etc. Using the data obtained by these parametric studies, next year's group will iron out the details on orbital mechanics, power, and propulsion systems. Further work will be done in order to realize the subsystems and their impact on orbital mechanics, power, and propulsion. For instance, when the control system study is accomplished, a power budget as well as a propulsion system and restrictions on the orbital radius for the spacecraft dynamic stability will be forthcoming.

As always, with more insight and information gained from new members as well as old, many changes and improvements will be in the works for next year. This is all a part of the design process, and the design that has been accomplished will continue in the near future.

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